Mill vibration during cold rolling

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Introduction

In common with other rotating machines, rolling mills are prone to many different vibrations during rolling and most do not cause a problem. However, there are several types of rolling mill vibration that can have a significant impact on the quality and/or productivity of the cold rolling process. This article describes the common types of cold mill vibration that can cause problems during the rolling of steel and aluminium sheet, including third octave and fifth octave chatter. 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.

Vibration Theory

The amplitude of motion of a machine in response to a cyclic exciting force, sometimes referred to as the flexibility of the machine, depends on the frequency of the cyclic force relative to the natural resonant frequencies of the machine. For example, if the exciting frequency is equal to a natural resonance frequency then the amplitude tends to be large because the machine is very flexible at resonance. In this case the amplitude is limited by the damping associated with the resonance. If the exciting frequency is below or above the natural resonance frequency then the amplitude is significantly smaller and inversely proportional to the stiffness or mass of the machine, respectively. Typically, most damaging vibrations involve a natural resonance of the machine which significantly increases the displacement of critical components, for example the rolls of a mill.

Another important concept to understand is that of 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 famous example of self-excited bridge vibration is the Tacoma Narrows bridge in 1940 shown during vibration in figure 1. Here, aerodynamic instability at high wind velocities produced extreme amplitudes of structural vibration ending in the destruction of the bridge. It is important to note that there was no independent external cyclic force exciting this structure. The force that sustained the vibratory motion came from the motion of the bridge itself, requiring only a small initial disturbance to get it started.

Figure 1: Tacoma Narrows bridge during self-excited structural vibration in 1940

Third octave gauge chatter, one common type of mill vibration, falls into this self-exciting category. The physical mechanism that produces the sustaining alternating force relates to the continuity of mass flow through the mill bite. Like the bridge, the mill will vibrate without an independent external cyclic force to excite it.

It should be noted that the terms third and fifth octave relate to the definition of musical frequency ranges and were used historically to distinguish the two problems.

Types of Mill Vibration

(a) Low Frequency Forced Vibrations

The simplest type of mill vibration is found in all mills and is a forced vibration such as that due to roll eccentricity. 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 of the mill and material being rolled. This type of gauge variation can represent a significant proportion of the total gauge variation of the product delivered to the customer. In some cases it is possible for this vibration to be worsened by excitation of torsional resonances of the main, unwind and rewind drivetrains of the mill.

Typically the resonant vibration modes of a rolling mill involving translational motion of the rolls have frequencies greater than 50Hz. If excited, most of these modes will not be detrimental to rolling but some specific modes can be very damaging to mill productivity and/or product quality. These modes are responsible for the main types of what is termed ‘mill vibration’ and are described below.

(b) Third Octave Gauge Chatter Vibration

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 many 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 will also be felt through 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 2 shows the typical rolling mill resonances that can become excited to produce gauge chatter[1] . 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.

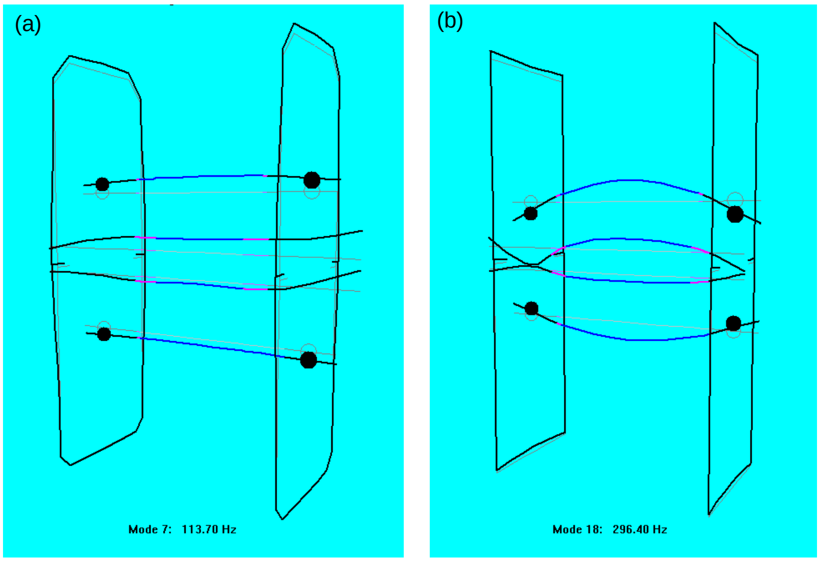

Figure 2: Typical mode shapes of rolling mill resonances that become excited during third octave gauge chatter. (a) shows the most common mode with a frequency between 100 and 150Hz and (b) shows a less common higher frequency mode. The lines represent the central axes of the rolls and housing frames in a 4-high mill[1].

As stated earlier, this type of vibration is self-exciting. 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.

$$H_i \, V_i = H_o \, V_o \qquad ...[1]$$

where H_i and H_o are the entry and exit gauges and V_i and V_o are the entry and exit strip speeds. Figure 3 illustrates this mechanical feedback loop that exists in every mill stand[2] .

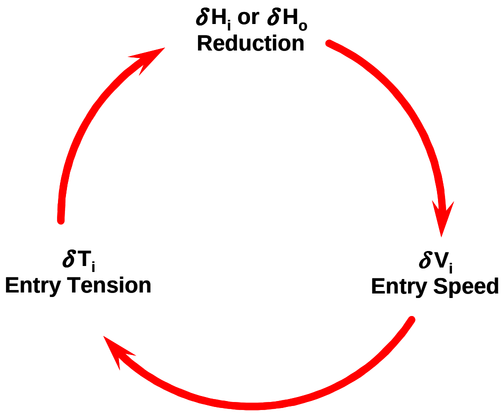

Figure 3: Mechanical feedback loop that exists in every mill stand with the potential to cause self-excited third octave gauge chatter.

On the basis of continuity of mass flow through the mill stand during rolling it can be shown that a change of exit gauge will produce a change in entry strip speed, assuming the entry gauge and exit speed remain constant.

$$\delta V_i = \frac{V_o}{H_i} \delta H_o \qquad ...(2)$$

The change in strip speed at one end of the entry strip compared to the other, V_c, will produce a change in entry strip tension, T_i, as follows

$$\delta T_i = K_s \int (\delta V_i - \delta V_c) dt \qquad ...(3)$$

where K_s is the stiffness of the entry strip given by the following equation

$$K_s = E \frac{W H_i}{L} \qquad ...(4)$$

where E is the elastic modulus of the material being rolled, W is the strip width and L is the length of the entry strip over which the speed difference was applied.

A change in entry tension will produce a change exit gauge thus completing the loop as follows

$$\delta H_o = \left(\frac{\partial H_o}{\partial RL} \right) \left(\frac{\partial RL}{\partial T_i} \right) \delta T_i \qquad ...(5)$$

where RL is the rolling load. The ratios in equation (5) are roll gap sensitivities that will depend on rolling variables such as the roll gap friction.

There is a 180 degree phase change around the feedback loop in figure 3, 90 degrees coming from the mill vibration mode and 90 degrees from the integration required to convert strip velocity to tension in equation (3).

Analogous to electrical control system instabilities, if there is a 180 degree phase change around the loop then the loop will go unstable as the gain is increased above a certain threshold value. From the above equations coupling each term in the loop it can be seen that gain is proportional to the exit speed of the strip (equation (2)). 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.

It is possible to formulate the above feedback equations in the Laplace domain and to then apply a standard condition for the threshold of self-excitation. This results in the following equation for the rolling speed at which the mill would start to vibrate[3].

$$V_{critical} = \frac{-2 L M_{eq} \zeta \omega_n^3}{\frac{dF}{dT_i} E W} = \frac{-2 L \zeta \omega_n^{3/2}}{\frac{dF}{dT_i} E W M_{eq}^{1/2}} \quad \text{...(6)}$$

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.

The problem is more complex in cold tandem mills as each mill stand will exhibit the mechanical gauge chatter feedback loop and these loops will interact as shown in figure 4. If a downstream mill stand starts to exhibit gauge chatter then the change in entry tension will be felt by the previous mill stand as a change in exit tension. This change in exit tension can excite the upstream mill stand to vibrate. If the upstream stand vibrates it will produce an exit gauge variation which will travel with the strip and will excite vibration of the downstream stand.

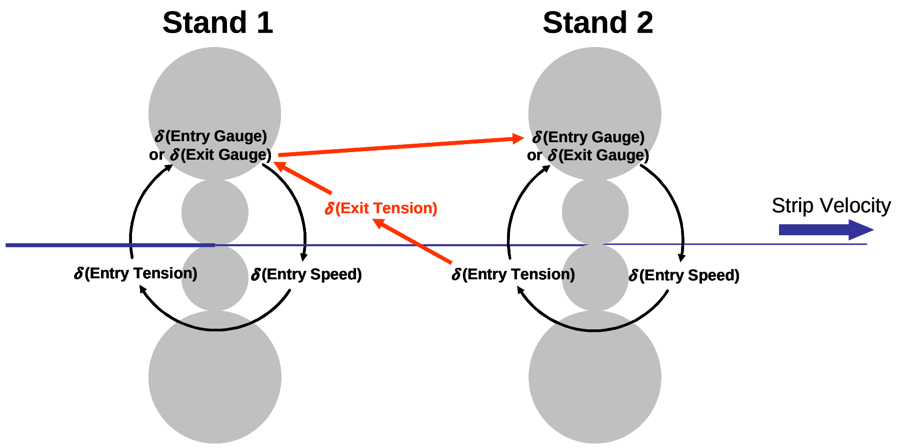

Figure 4: Interactions between two neighbouring stands in a tandem cold mill during mill vibration showing feedback of strip tension variation and feedforward of strip gauge variation.

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.

From equation (6) it can be seen that the critical speed of a rolling mill limited by third octave vibration can be increased by

(i) increasing the length of the entry strip

(ii) increasing the damping associated with the chatter mode

(iii) increasing the frequency of the chatter mode

(iv) decreasing the mass of the chatter mode

(v) decreasing the sensitivity of rolling load to entry tension

In the case of the entry strip length, in principle this is correct. However, the situation is more complex due to the presence of other mechanical equipment such as entry rolls that can interact with the main feedback loop in a positive or negative way. Increasing the damping is a text book approach to this type of problem and can be achieved in passive and active ways. The sensitivity of rolling load to entry tension can be affected by rolling variables such as friction.

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 very 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 5 shows an example of severe chatter marks around the barrel of a backup roll before grinding[4] . 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.

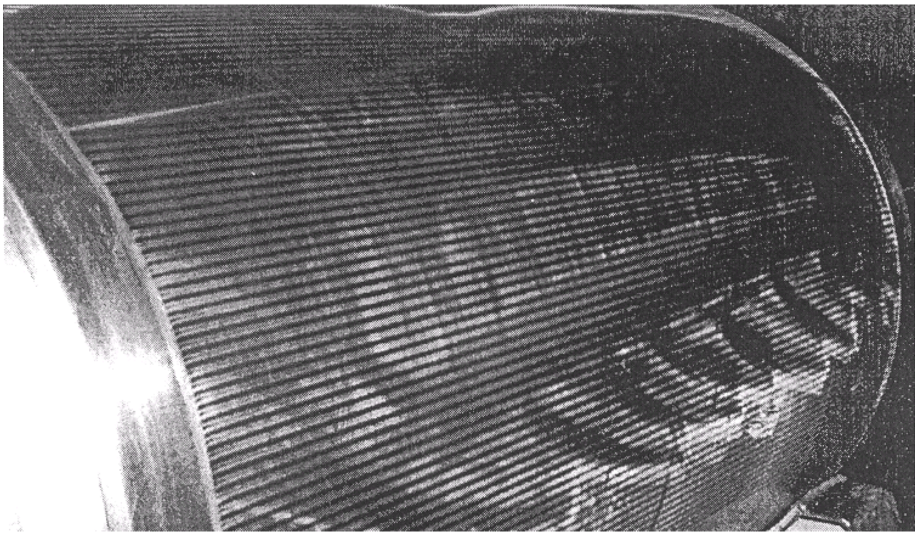

Figure 5: Example of severe fifth octave chatter marks on the barrel of a backup roll that would produce similar surface markings on the strip[4].

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 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.

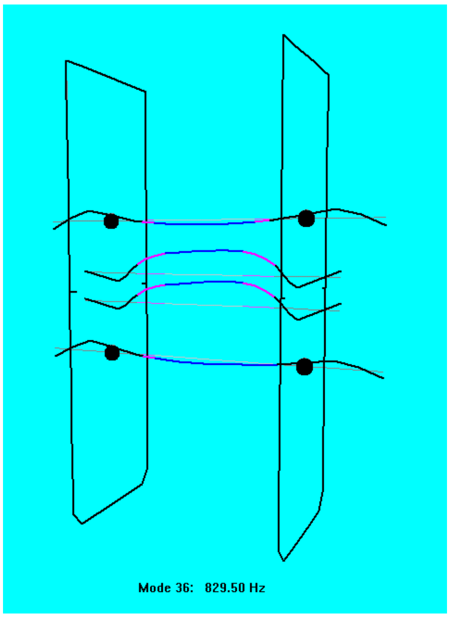

Figure 6: Typical mode shape of a rolling mill resonance that can become excited during fifth octave chatter. The lines represent the central axes of the rolls and housing frames in a 4-high mill[1] .

Figure 6 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 evidence linking this mode to roll and strip marking is presented elsewhere[1],[4]. 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. This usually involves careful experimental vibration measurements.

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, 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.

The topics mentioned in this article are covered in Innoval's new Aluminium Rolling Technology Course. This 4½ day course is suitable for engineers working in the aluminium production and processing industry and covers the important aspects of hot and cold rolling of aluminium flat products. Please contact the author for further information on how this course can help to improve your productivity and product quality.

References

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[2] Evans, P.R., Hill, D.E., and Vaughan, N.D., "Dynamic Characteristics of a Rolling Mill", Proc. Instn. Mech. Engrs., V210 (1996), 259-271.

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