

Executive Summaries

A brief description of each problem is given followed by the equation-free Executive Summary for the problem

ANALYSIS OF LUBRICANT BEHAVIOUR AND ROLL DEFORMATION DURING COLD ROLLING OF STEEL

Columbus Stainless Steel

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Description

- During cold rolling of steel, the steel is passed between two rollers and lubricant is therefore dragged through the gap. The load on the rollers causes the steel to deform plastically, the rollers are likely to deform elastically. The process leads to an increase in temperature in the rollers and the lubricant. The lubricant undergoes high pressure and temperature changes and its properties may vary significantly throughout the contact. There seems to be plenty of recent numerical work on cold rolling including variable viscosity, thermal effects, elasticity and plasticity. These papers were forwarded to Columbus.

Executive summary

- Lubricant behaviour: The viscosity of mineral oils, which are frequently used as lubricants, varies significantly with pressure and temperature. A standard model for the behaviour is the modified Barus law. This shows that the viscosity decreases exponentially with pressure and exponentially with temperature (obviously within certain bounds for pressure and temperature). Since steel deforms plastically at a pressure of 200Mpa it was assumed that the fluid pressure never exceeds this value. The temperature of the oil can be measured at the outlet and a temperature increase of 40°C is expected. Using these values it was shown that the viscosity will increase by a factor of 55 due to pressure effects and decrease by a factor of 5 due to temperature. Clearly then both of these effects need to be accounted for in any reliable model. However, it is the pressure viscosity effect that is dominant.

Right contact, pressure dependent viscosity model: A good starting point for the modelling of a lubricated rolling contact is the simple rigid rollers/substrate model. This gives an indication of the pressure and fluid behaviour within the contact. We developed a model of a roller (using the standard quadratic

approximation to the roller within the nip) separated from a moving flat substrate by a thin film of liquid.

The difficulty in modelling this type of contact is that the extent of the nip region is unknown 'a priori'. It has been found that by imposing zero pressure and zero pressure gradient at the outlet (a cavitation condition) the end of the nip can be determined quite accurately, see [1, p.329-331], [2] for example. From this model, if we know the fluid flux (which can be measured at the outlet) and the yield stress we can estimate the film thickness in the nip. We did not have data on the flux, so could not test this, but at least a model is in place which can be subsequently used. Further, it allows us to test the effect of surface roughness on the pressure. This was briefly investigated during the week and it was shown how small perturbations on the roller produced small perturbations in the pressure. Further work is needed on this, in particular using realistic flux and surface roughness data.

Rigid contact, pressure and temperature dependent viscosity model: A model was also investigated with the temperature variation with viscosity included and shear heating within the film. A significant conclusion of this model was that the shear heating was not the cause of the temperature increase within the lubricant. Consequently the temperature rise must be a result of the plastic deformation. This conclusion simplifies the temperature calculation within the oil film: it can only vary linearly across the film.

Plasto-hydrodynamic model: We began by considering the plastic deformation of the steel. The presence of a lubricant means we can neglect friction and so end up with a simple relation between the two principal stress components and the yield stress. Physically this states that we can make the steel flow either by pulling it or compressing it.

The full plasticity model was not successfully solved during the week. However, this was due to time constraints and not to some intrinsic modelling issue. The model involved splitting the contact into three regions:

- an inlet where fluid pressure is moderate and so a hydrodynamic model is appropriate (i.e. no solid deformation);
- a work zone where pressures are high and the steel shape approximately follows the roller shape, the oil film satisfies a high pressure (variable viscosity) lubrication equation;
- an outlet where a hydrodynamic model applies and the steel stays at its final thickness.

Whilst we determined solutions in each zone, the correct matching was not obtained during the meeting. This work is ongoing.

Future work: In the final report it is hoped to clarify all the above models and in particular sort out the matching in the plastic model. This will provide a simple tool for analyzing cold rolling (as opposed to the complex numerical models of the existing literature).

Reference

- [1] Johnson K.L. *Contact mechanics*, Cambridge University Press, 1987.
- [2] Cameron A. *Basic lubrication theory*, Halsted Press, 1981.

PISTON EFFECT DUE TO ROCK COLLAPSE

Mining Industry

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Description

- When there is a collapse of rock in an underground excavation, the collapsing rock usually displaces a large volume of air and this displaced air can result in an air-blast. Air-blasts are extremely hazardous occurrences and can cause death and damage to mining equipment and infrastructure. Very high air velocities can be attained. There are several questions that arise in this connection:
 - a) The collapsing rock represents a porous piston. How easily can air escape through the gaps between rock blocks and what is the percentage effectiveness of the piston?
 - b) How would the flow of air best be modelled?

There is usually interconnection of an underground excavation via tunnels and shafts to other underground excavations, with different surface roughness, and one or more connections to the atmosphere. The rock collapse may cause a break through to the atmosphere. Minor air-blasts are a common occurrence in some coal mines.

Executive summary

- The study group considered a rock fall in a cavity with one tunnel connected to it. The problem was broken up into two parts. The first was to model the effect of the rock fall on the pressure in the cavity. In the second part the gas dynamics in the tunnel was considered.

The problem of how to model the rock fall is quite complex. The study group considered various models which varied in complexity, the simplest being to

regard the falling rock as an impermeable piston. It was found that the rock fall occurred on a time scale much shorter than the time needed for a shock wave to form in the cavity and therefore shock waves did not have to be considered. The models allowed the group to find expressions for the pressure in the large cavity. Although details of how the rock falls are not known, the simplest model gives a worst case scenario. The models showed that if the tunnel is in the upper region of the cavity, the pressure increase can be quantified but is relatively small. The question of the "percentage effectiveness" of the piston is still an open research problem and very little data exists.

If one knows the pressure in the cavity and therefore at the entrance of the tunnel, the flow in the tunnel can be modelled by the Fanno model, for turbulent compressible flow, provided the tunnel is long compared to its cross sectional circumference [1]. The simplest case, where the pressure at the mouth of the tunnel is a constant and only a little above ambient, was considered and it was shown that a "snow plough effect" occurred where the pressure stayed elevated over an extended period of time before it dropped off to atmospheric pressure. This would cause a very high velocity wind, which could last for a long time (several minutes), to move down the tunnel. This wind is definitely capable of causing serious damage as was observed in the examples presented to the study group.

References

- [1] Ockendon, H., Ockendon, J.R. and Falle, S.A.E.G. "The Fanno model for turbulent compressible flow," *J. Fluid Mech.* 445 (2001), 187-206.

PREDICTION OF LIME QUALITY AND CARBON MONOXIDE LEVELS IN A LIME KILN

Optin, Supplier of Optimal and Intelligent Solutions

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Description

- For the production of lime from limestone, the operator wants to predict, and eventually control, the quality of lime that is produced; one aspect of “quality” is the proportion of limestone converted to lime. In this process, limestone is fed into an inclined industrial kiln which rotates at a rate that can be adjusted; as the rotation takes place the limestone progresses down the incline. The kiln is heated internally through the burning of coal powder, supplied at the lower end, which burns in a flame zone. Another important aspect of the process is the effectiveness of the burning of the coal partly because this helps to determine the efficiency of the lime-conversion process and partly because incomplete burning is associated with the release of carbon monoxide, which is highly undesirable in its own right. Currently the carbon monoxide levels are measured by gas recording equipment. However, these values are known to be inaccurate for a number of physical reasons.

Executive summary

- The study group proposed two approaches to the problem in the hope that there would be an intersection of the chosen methods. The first was to derive a model for the process as a system of equations, starting from first principles. The underlying laws used are those of energy and mass conservation and are combined with rate equations for chemical reactions. If we then know the temperatures of the gas and limestone as they enter and supply rates of limestone, coal powder and gas, we should be able to derive what the expected lime output will be and hence the quality of the lime itself together with burning efficiency. As a simpler first try at modelling, the coal burning was regarded as known; this gives no information regarding efficiency.

The second approach proposed was with regard to the measuring the carbon monoxide only. The gas recording data can be examined purely from a data perspective, ignoring the physical aspects of the problem. Due to the nature of the data, Fourier analysis does not yield anything meaningful. Instead, the approach to be taken is that of Wavelet analysis, where the repetition of the transform is dependent on the scale and position of the wavelet. Like Fourier methods, high frequency and low frequency filters are applied to the data to transform seemingly randomized data into giving the underlying pattern of the data.

OPTIMAL SCHEDULING AND LOADING OF TRUCKS FOR DISTRIBUTION OF SOFT DRINKS

Amalgamated Beverage Industries

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Description

- The problem is concerned with the optimal scheduling and loading of trucks for the distribution of soft drinks. The Study Group was asked to work out an optimal configuration of truck load that will enable savings on offloading and to increase the number of loads per truck thus saving on truck hire costs.

Executive summary

- Given that the company is satisfied with the current software (Road Show) in as far as meeting the objective of allocating a prescribed group of customer orders to a particular truck for a particular route, the group reached a consensus that in order to meet the objectives of maximising the number of trips per truck per day and minimise the offloading time per truck, the following two questions should be addressed. Firstly, whether a truck can be packed in such a way that the unloading procedure consists only of removing cases from the top of the multi-stack? Secondly, if this is possible, can this be done to minimise the packing effort?

To answer the first question requires the use of the available information regarding delivery sequence of the orders, which is assumed to be currently not utilised. The worst case scenario of mixed pallets was considered since it is the most difficult. However, while answering the first question could result in substantial savings on costs for offloading, it is possible that it will impact on the picking and packing time. The idea is to try and answer the first question by making use of the prescribed delivery sequence, as well as the available data on the stock keeping units (SKUs) of the various products. This would be achieved by working out an optimal configuration of the truck load that will enable savings on offloading. This procedure would be based on a simulated-annealing algorithm used in global optimisation. Once this

configuration has been worked out, it is reckoned that focus would then be turned to the picking and packing process, particularly at the staging point. It may be necessary to change the current picking list in a way that may require pallet-based picking and packing instead of the current product-based approach. At the end of the exercise, the procedure should try and balance the costs of picking and packing against the costs of offloading time. If a good balance is reached, it is hoped that the objective of increasing the number of trips per truck will be met, thus saving on truck hiring costs.

At the end of the week some simple code for some possible criteria and/or penalties that should be incorporated into the model had been identified. These remain to be combined and then used with the simulation algorithm to work out optimal truck load configurations. The results of the simulations will be included in the report to be submitted later.

DETERMINING THE SOURCE OF MOISTURE VARIATION IN PRODUCED PAPER

Sappi Forest Products, Ngodwana Mill

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Moderator

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Description

- Sappi Forest Products produces paper boxes. Paper consists of bonded discrete wood fibres laid out in a sheet and is produced from a dilute water suspension of fibres by 'ponding', draining and drying. Variation in thickness, moisture content and density in the sheet of paper produced by this process (in our case a long roll of width 6m) can cause defects in the final product. Moisture variations (streakiness) across the paper sheet are of particular concern to Sappi. Such variations in moisture content are usual, however, excessive variations are unacceptable. On-line moisture scanners have been used to detect the problem and hopefully will lead to appropriate corrective adjustments of the machinery. The moisture variations of interest can originate at one or several stages along the process; the latter is more likely the case so that it is a matter of identifying and correcting major problem areas. Sappi asked the group to examine the data to 'determine the number and the sources' in the hope that machinery problems could be identified.

Executive summary

- The moisture profile across the paper width appears to exhibit a relatively large amplitude (2%) short wavelength (about 20cm) periodic variation superimposed on a small amplitude long wavelength (perhaps 1m) variation. A spectral analysis of this data was undertaken and revealed a more detailed/complex picture with a broad range of harmonics (and sub-harmonics) present. Details will be provided in the final report. One possible cause for moisture variations lay in the geometric arrangement of nozzles in the head-box. Sappi changed this geometric arrangement of nozzles to possibly achieve a more uniform flow within and from the head-box and thus a better product. Significant improvements did not seem to result and at least visually there appears to be no obvious change in the moisture pattern. A spectral analysis revealed that significant changes in the

moisture profile did in fact occur, although the changes were not beneficial. The length scale of 'the short wavelength modes' increased as a result of the changes, although there was no significant change in the amplitude of these modes. The actual wavelengths involved are larger than the spacing between nozzles, so that the link between the spacing and the moisture variations is not obvious. Possibly the wavelength of a fluid dynamic instability mode is modified by the changed forcing. All this suggests that head-box design is important but there may be no obvious simple fix; it is the combined effect of various features of the flow and the geometry that determines the outcome. The moisture spectrum has the breadth normally associated with turbulent phenomena. It may also be the case that the slurry properties play an important role. The group felt that further data investigations of the type undertaken at the meeting would be both useful for the present investigations and for straight quality control purposes.

In order to correct the problem one needs to locate it and then one needs to understand its basic physical/chemical cause. Whilst this was not part of the brief the group attempted to identify possible causes. The most likely problem area is in the sheet formation zone. The dilute (0.35% fibre) slurry is fed from the head-box, through a flow spreader (20mm high, 6m wide) and onto a fine screen belt moving with a speed of about 1m/sec. Water drains from and is also sucked from the suspension, so that at the end of the zone (15m long) one is left with a layer of wet fibres roughly 1mm thick. Any non-uniformity introduced during this process will be reflected in the final product. Subsequently the paste is pressed (by passing through rollers), dried, and the paper sheet rolled up. The final sheet contains 4-10% moisture.

Immediately before leaving the head-box the slurry needs to be turbulently stirred (and diluted) to prevent flocculation and possibly separation out of fibre types. However immediately after the slurry discharges onto the belt quiescent conditions are ideal; any leftover turbulent mixing will result in a nonuniform paste thickness which will in turn effect the moisture profile. (The careful 'matching' of the belt and flow speeds is thus required and is achieved by adjusting the pressure head in the head-box). The before and after conditions described above are of course incompatible and this is possibly the origin of the difficulties. This means that one needs to design and tune this system carefully. Turbulent rolls generated within the head-box damp out slowly, sharp edges shed eddies, and end effects associated with the flow spreader can initiate instabilities and cause fibre orientation difficulties. The angle of flow entry onto the belt is critical; a small entry angle will tend to lead to the smoother flow desired on the belt but may allow flocculation. All such flow effects will cause surface waves which in turn will result in paste thickness variations. Additionally, small differences between the belt

and flow speed can generate instabilities commonly associated with paint spreading problems. The above possible sources of difficulty all have their own particular signature which may be identified, but more detailed information about the factory operation would be required to do this. An attempt to quantify the various effects was made at the meeting and results will be presented in the final report.

SUPPORT TO ROCK EXCAVATIONS PROVIDED BY THIN ADHESIVE LINERS

Mining Industry

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Description

- Shotcrete has been used for support of excavations in rock for about fifty years. The design of such support is usually based on the assumption that the liner acts as an arch. However it is known that thin applications of shotcrete (10 – 20 mm) provide a significant supporting or stabilising effect. Recently, the use of thin spray-on liners, typically 4mm thick or less, for rock support has increased. No arch action can be claimed in such a case. There is no suitable design method for thin liners that can take into account the numerous possible support mechanisms and their relative contributions. One factor that is perceived to be very important is the contribution of the liner to the prevention of loosening of the rock mass, therefore maximising the shear strength mobilised on the rock joint and fracture surfaces. The Study Group was asked to develop a mathematical model for thin adhesive liners.

Executive summary

- A T shaped geometry was used to model the region consisting of the joint between two blocks of rock and the liner. The vertical part of the T represented the joint and the cross bar represented the liner material. Anti-plane strain theory was applied, purely for the purposes of simplifying the exposition. The stress tensor has only two non-zero components and the displacement vector has only one non-zero component which, from the equations of static equilibrium, satisfies Laplace's equation in the two blocks and the liner. It was assumed that there was no traction at the joint although further developments of the model would be to include friction of the joint and to allow the liner to penetrate the joint. The stress concentration at the joint tip adjacent to the liner was analysed. For a high shear modulus contrast between the rock and the liner material there is a strong stress singularity at the joint tip that may be as great as $1/r$ where r is the distance to the joint tip. The strong stress amplification in the liner near the joint is independent of the liner

thickness and depends only on slippage on the joint for a weak liner. Further insights into the joint-linear interface interaction could be obtained using an appropriate numerical solution, looking at other asymptotic regimes and extending the model to plane strain.

CUSTOMER SATISFACTION UNDER CHANGES TO A DISTRIBUTION NETWORK

Amalgamated Beverage Industries

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Description

- Stock distribution is the management of the storage and delivery of goods. It involves customers, delivery vehicles (with crews), warehousing and manufacturers. It presents a wide range of scheduling, queuing and Optimisation problems. ABI presented a problem associated with change in the distribution network. Before the change, there was a single distribution centre A, supplied from distant factories and supplying customers over a large region. Then it split into two and after the change, there were two distribution centres A and B. Centre A lost some (distant) customers to centre B. The expectation was that the increased capital and running costs would be more than offset by reduced transport costs.

Unexpectedly, out-of-stock events are occurring at B. Our task was to understand this. In particular, we must consider the possibility that ABI's safety stock policy at B is inadequate. It was suggested that the predictions of safety stock were too low.

Executive summary

- Out-of-stock events at B are *not* due to inadequate safety stock predictions. Safety stock levels were impossible to maintain at B because the warehouse is too small and times between deliveries are too long. Company safety stock policy was not actually tested. Instead, out-of-stock events at B were to be expected, as levels of stock were inadequate by company standards.

This is not to say the safety stock level predictions are adequate, nor that the company policy for large distribution centres is also best for small ones. It is clear that smaller distribution centres may be more vulnerable to volatility in demand. This can be tested by means of mathematical modelling. We propose a calculation of the probability of out-of-stock events with the following components:

- Realistic aggregate customer orders (using real ABI data to model demand which must include correlation in demand between different products)
- Realistic constraints on warehouse capacity and delivery capacity.
- A safety stock management procedure (the actual ABI procedure, a procedure based on perfect knowledge of the statistics of the demands, and perhaps others).

Direct simulation is not the best way to proceed. Instead we will formulate the problem as one of Bayesian estimation, for which the standard approach to computation involves Markov Chain Monte Carlo (known as MCMC) algorithms. We will also pursue optimisation algorithms, which in some cases are themselves MCMC.