A MULTIPLE PARTICLE FEED CONTROL SYSTEM

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This paper describes the design and implementation of a multiple particle feed control system for a vibratory feeder, using vibration feedback to linearise the feeder, and optical particle detection in a cascade control loop. Start-up and shut down conditions were dealt with using a control sequence.

Keywords: Vibration measurement, Optical feedback, Simulation, PI controllers, Cascade control

1. INTRODUCTION

Test work and a recommended solution to inconsistencies in the performance of a particle feed system were carried out using a system mock-up, assembled to simulate a feeder in a De Beers plant. Problems had been encountered with the existing system due to temperature related performance drift, feeder non-linearity, and variations in the shape and size frequency distribution of the particles. Difficulties were encountered with excessive feed to the downstream process, since overloading of the process results in ineffective classification. Underfeeding results in excessive processing time.

2. BACKGROUND

The goal was to provide an even feed to the process to maximize classification efficiency – yet minimize processing time. An Eriez controller module and vibratory feeder were used, while control action was provided through a Siemens PLC. The system mock-up made use of standalone controllers since it was not possible to obtain a PLC for testing. The test work consisted of two phases, the first being to correct the non-linearity and temperature drift in the feeder, and the second being to measure and attempt to control the particle flow rate. In the first phase a Balmac vibration transmitter was fitted, and a closed loop PI controller was designed using the root locus method so that the response would produce less than 5% overshoot in all parts of the operating range.

Having linearised the feeder behaviour it was now possible to include it in a cascade control loop to control the particle feed. The particle feed rate was estimated using a Banner optical sensor, using an infrared beam to trigger a one-shot digital output. To make the output useful to the controller (requiring an analogue input), a first order low pass analogue filter was added. The low pass filter was designed in such a way that when a 50% duty cycle is encountered, the output would be 5 volts of the 0 to 10 volt input range to the controller. The filter parameters were adjusted in a Matlab Simulink Simulation until the upper and lower edges of the envelope were within 1% of each other, as well as providing a reasonable first order response. The optical sensor does not detect every particle, but detects how many times particles break the beam. It was found that this was suitably representative of the number of particles passing through the beam. The outer PI loop of the cascade controller was adjusted by observation so that the particle feed was suitable. It was found that the initial period, of moving the particles to the mouth of the feeder, and the final period of clearing the feeder of particles could not be catered for by this controller. A sequence was introduced to detect when a certain particle flow rate was achieved before switching over to automatic control, and returning to manual operation in order to purge the feeder, and avoid contaminating the next batch. The final system was implemented using a digital filter and a PLC counter card to replace the analogue filter. The system is producing good consistent results. The interesting conclusion is that a heuristic (non-linear) outer loop is more effective in dealing with the start-up and purging operating regions, but that cascade linear control works well under normal operation.

3. SYSTEM DESCRIPTION

The system consists of an input bin that discharges into a feeder tray. The feeder tray is shown in Figure 1.

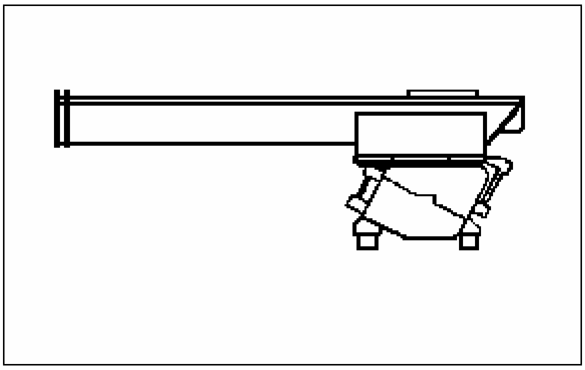

Fig. 1. Vibratory Drive and Feeder Tray

The vibratory drive is an Eriez HS-42 feeder, driven from an Eriez FEA-230 controller, accepting a 4-20 mA, or 0-10 V input. The end (mouth) of the tray is fitted with a Banner optical sensor to detect the presence of particles. The feeder tray has a bracket at the rear, where a Balmac vibration transmitter is fitted.

4. VIBRATION AMPLITUDE CONTROL LOOP

It is necessary to control the feeder vibration amplitude so that it tracks the setpoint over all conditions. The conditions (disturbances) that need to be catered for can be split into four categories:

1. Variations in calibrated or set-up range and zero.
2. Variations in feeder behaviour with time (ambient temperature, coil temperature)
3. Variations in load (amount of material present, interference, variations in tray manufacture/springs)
4. Non-linearity in the feeder controller module.

The ideal is to be able to roughly set up the trim-pots on the controller module, and then to allow the vibration feedback to ensure that similar vibrations are always achieved for the same control setpoint, as well as removing the non-linearity in the system.

The feeder displacement range was set up using a graphical displacement indicator provided by Eriez. The indicator is attached to the feeder along the axis of vibration, and allows the peak displacement to be read off at various input settings. Table 1 shows the selected calibration settings.

Table 1. Calibration Settings

Input (mA)	Output (V rms)	Displacement (p-p mm)
4	80-90	<1
20	180-190	2

These settings are recorded for future use if either the controller module or feeder drive are replaced. The calibration is carried out with an empty tray, and with a feeder that has been allowed to run for 20 minutes to ensure that the coils are warm. The values from the graphical indicator were also confirmed against the vibration transmitter, which has a range of 0 – 10 inches per second (peak-to-peak). The vibration transmitter is fitted horizontally, whilst the graphical indicator is at an angle of 24.65^{o}. After making the necessary compensation the transmitter and graphical indicator were found to be in agreement.

Open loop step tests were carried out to determine the time constant and gain of the system, and the results are shown in Figure 2.

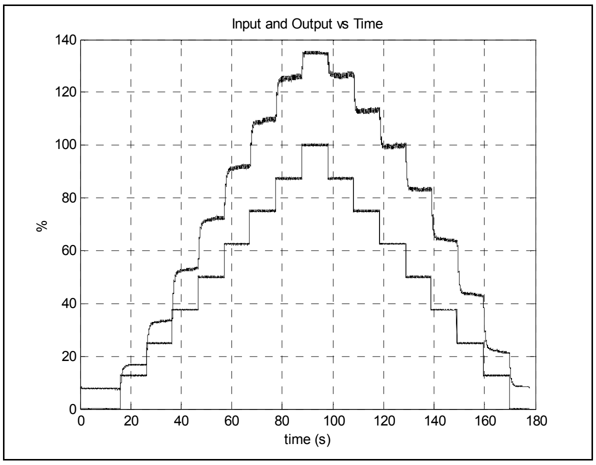

Fig. 2: Input mA (lower trace) and Vibration Output mA

There are a number of features of interest in this graph.

a. There is an offset in the output from the Balmac (0.075 %). This is due to the fact that the vibratory feeder becomes active at around 2 mA, so that by 4 mA there is already a signal present on the vibration transmitter.
b. The gain is non-linear, and increases with the percentage input.
c. The gain and step response are different when stepping up, and when stepping down.
d. The output of the vibration transmitter is about 35% over range (i.e. up to 135%). This is not a problem since the vibration transmitter will not be damaged, and the region of control interest is

in the range between 10 and 30%. Under control the system will not exceed 100% (except for some overshoot if it is present)

The approximate transfer function for this system is given by:

$$P_v(s) = \frac{1}{0.9s+1} e^{-0.56s} \qquad (1)$$

The delay in this transfer function includes the delay from the ERO PKC standalone controller. The input sampling period of the controller is 125 ms, the output update time is 125 ms and it appears as though the controller takes about three cycles (3 x 125 ms) to update the output with a change in response to a setpoint step-change. A (1,1) Padé approximation to the delay component was used in order to plot the root locus. The root locus for this transfer function is shown in figure 3.

From the root locus, suitable gain values appear to be those in the range of 0.35 to 0.55. The overshoot starts becoming significant at around 5%, and it is preferable to keep the gain down toward 0.4, where the overshoot is closer to 2%. Also we have to bear in mind, that the non-linear gain of the feeder system will tend to push the system toward instability as the control input approaches 100%. Tests showed that although the dynamic response was suitable, the steady-state offset was significant (as expected). Using the following series representation for the PI controller in the system simulation the effects of integral action were evaluated:

$$C(s) = K_p(1 + \frac{1}{T_i s}) \qquad (2)$$

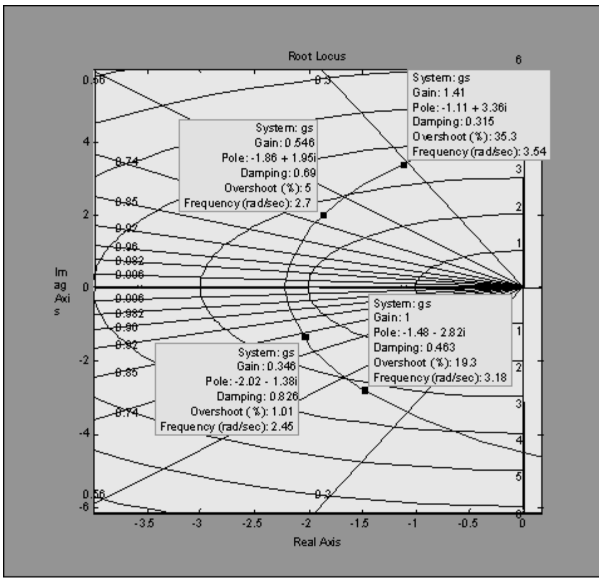

Fig. 3. Root Locus

Adding integral action to the controller countered the offset, and the system performed satisfactorily with the maximum integral (1s) added to the standalone controller. The simulations done using Matlab and Simulink, were found to agree with the behaviour of the standalone controller. The simulated and actual responses without integral action are shown in Figure 4.

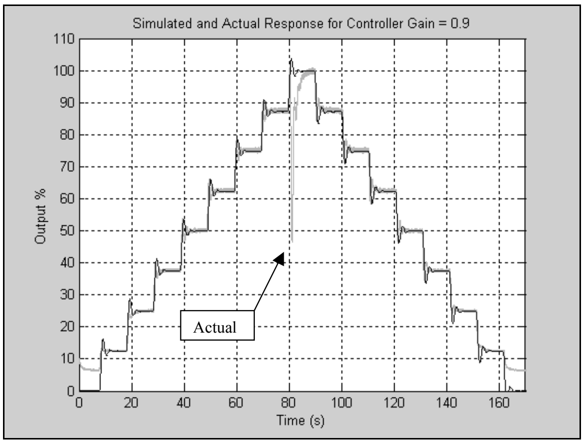

Fig. 4 Simulated and Actual Responses with no Integral

Figure 4 shows that the simulation provides a reasonable approximation to the system in the region of interest (between 10 and 30%). The simulation tends to overshoot more than the actual system except at the 100% setpoint step. That the simulation overestimates the actual system is acceptable (i.e. the system is more conservative than the model), and means that the controller design is on the conservative side. The ‘undershoot’ and cycling on the 100% step are due to a poor implementation of anti-reset windup in the standalone controller, and the suppliers expect that this is a fault in the system.

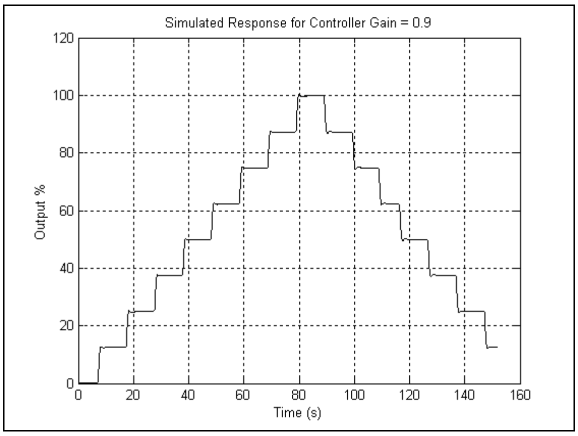

Fig. 5. Simulated Response with Integral Action

Figure 5 shows the simulated response with the addition of integral action. With a gain of 0.9 the system shows a very clean response with an

overshoot of about 5%.
The PLC controller was later able to provide better results because its delay is only 100 ms per cycle, and the 75 ms reduction in delay made the system more stable. A good overall response was achieved with an overshoot of between 2 and 5 %. The objective of linearising the feeder, and catering for performance variations with change in temperature and operating duration was achieved.

5. PARTICLE FEED CONTROLLER

The process value to the particle feed controller is taken from the Banner optical detector (also referred to as a light curtain). Figure 6 shows the location of the detector at the mouth of the feeder. The detector uses an infra-red beam, and produces a 24 V one-shot output pulse with a width of between 1 and 150 ms. The pulse width was set to a minimum to capture the passage of as many particles as possible. It was found that vibration of the feeder platform resulted in small displacements between the optical transmitter and receiver heads so that spurious pulses resulted. The sensitivity was adjusted so that vibrations and very small particles no longer triggered the output.

A simple first order passive RC filter was implemented to convert the pulse output from the optical detector to a useful analogue input to the standalone controller. It was necessary to use a voltage divider network to reduce the 24 V signal to the 10 V range of the controller input.

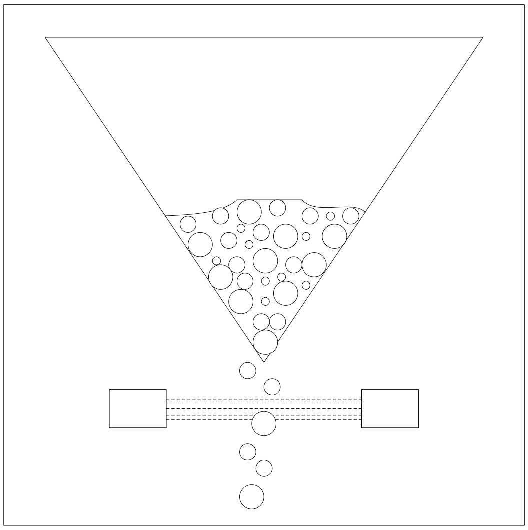

Fig. 6 Optical Detector

The filter was designed so that the analogue output would be 50 % (5 V) when the pulses are present 50 % of the time over some interval. A simulation was set up with marks and spaces of 1 ms each. With a filter time constant of the same order as the pulse width, the output is an approximate sawtooth wave that attempts to track the pulses. As the filter time constant is made longer, the troughs and peaks of the sawtooth wave approach each other. It was decided that the troughs and peaks should be within 1 % (of output scale) of each other. A time constant of 0.1 s (100 times the pulse width) resulted in a suitable response as shown in Figure 7.

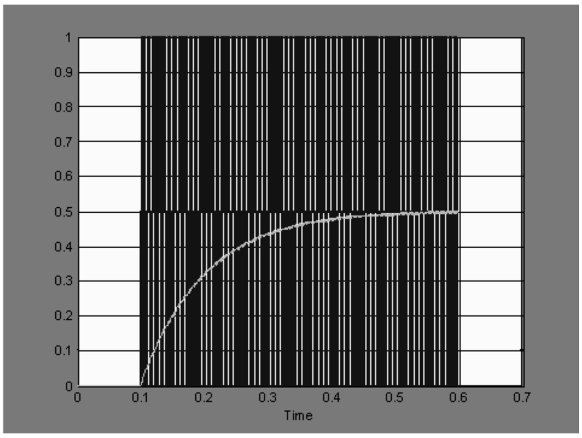

Fig. 7. Simulated Filter Step Response

The actual response compared very favourably with the simulated results.

From this point the feed controller was set up with the vibration amplitude controller in a cascade loop, with the basic layout shown in Figure 8.

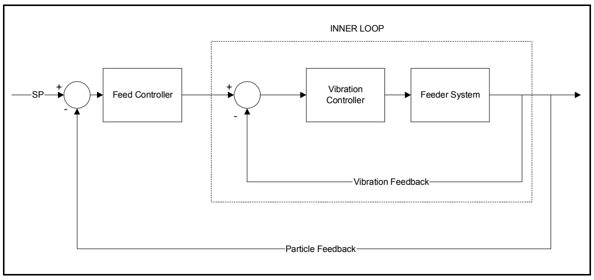

Fig. 8. Cascade Control Loop

The controller was tuned by first setting the gain to ensure a smooth feed at the desired setpoint. A second ERO PMC standalone controller was used for the outer loop. With a vibration setpoint of 13% it was found that the feed of the inner loop was acceptable, and this was selected as the point around which control would take place. The gain of the outer loop was set manually, and controlled suitably at a value of 0.3. Integral was then added, and a value of 12 seconds provided enough action to remove the steady state offset without the feed swinging around the setpoint. Listening to the sound of the feeder, the controller could be heard to be taking action when clumps of particles, or groups of either large or small particles were passing through the optical detector. When the feed was of particles of similar size the feed control was smooth and consistent.

Derivative action was later added to take care of gaps in the feed, where the integral action increases the setpoint to the inner loop. The derivative action was added so that the output is quickly reduced when particles are once again detected. A derivative value of 35 appeared to be optimal in this case. This action did not always achieve the desired result, since when the controller output had integrated above about 35%, the derivative action was not sufficient to pull the output down quickly enough or for long enough. Later the derivative action was removed, and a PLC sequence was used to take care of this problem.

6. PLC CONTROLLER IMPLEMENTATION

The controllers were implemented on a Siemens S7-300 PLC, and the analogue filter was replaced by a counter card with a maximum frequency of 200 kHz. The counter card was read at the same cycle time as the controller update (100 ms), and the filter was implemented in a difference equation format. The PLC performance of the controllers was improved, compared to that of the standalone controllers due to the reduction in the internal delay in producing control action after seeing a change in the process value (300 ms compared with 375 ms). The system became more stable.

There are three operating regimes in the control of a feeder. These are as follows:

1. Start-up, i.e. moving the material from the rear of the tray to the mouth of the feeder.

2. Controlled operation

3. Purging of the feeder tray at the end of the cycle.

One of the keys in this exercise is that the controller is only used to handle the normal operation of the feeder (i.e. excluding the start-up, and the purge of the tray). This is a batch operation, where start-up and purging represent a significant portion of normal operation. Attempting to use the controller to deal with start-up and purge as well, results in a very loose control strategy that does not provide good performance in any of the operating regimes. For this reason a control sequence was implemented to take care of the start-up and purge so that the controller could be optimised for ‘regular’ operation.

Patience must be exercised during start-up since it is tempting to run the feeder as fast as possible to get the particles to the mouth of the feeder as soon as possible. This is not a good idea! Figure 9 demonstrates the situations that arise.

A. Typical initial condition: Material has been dumped in the tray prior to the processing of the batch

B. The feeder is run as fast as possible to get the material to the feeder mouth as soon as possible. This results in a heap at the mouth, where the slightest vibration results in a flow of particles, making it very difficult to control.

C. A nice even layer of particles that allow the controller to function effectively.

D. Running the feeder too slowly results in too few particles at the mouth of the feeder. The controller will correct for this by adding integral action. This often results in condition B, since there is insufficient time for the controller to cut back, and this results in a massive over-feed.

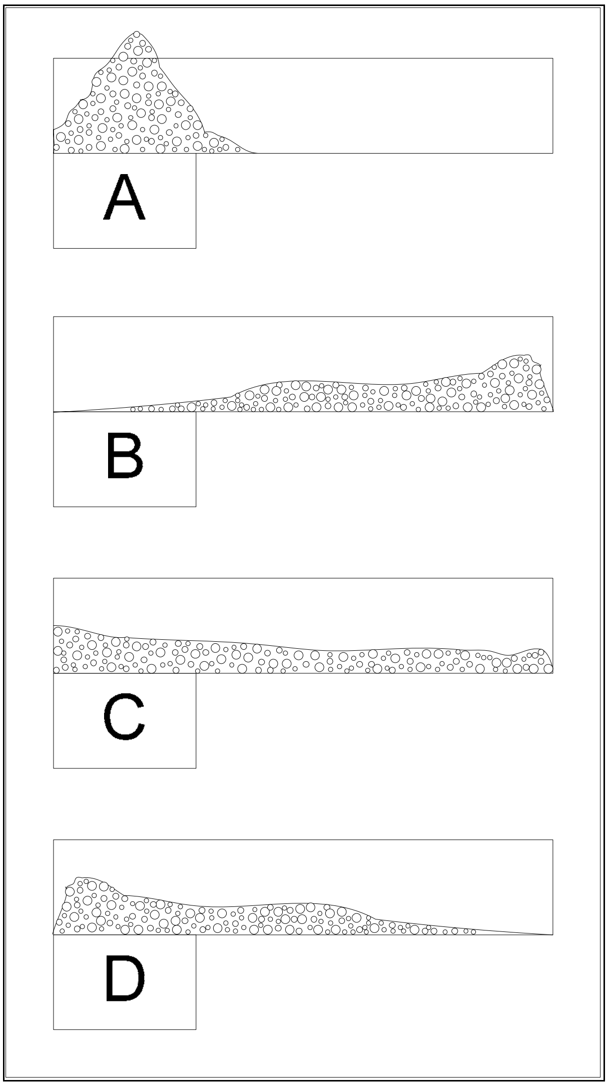

Fig. 9. Start-up Feed Scenarios

The idea is to aim for scenario C, so that the controller is able to get on with what it does best. A start-up setting is selected (through observation) - 13 % output in this case. This sequence is designed to operate in a number of states. These states are:

- Waiting to detect particles
- Waiting for enough particles to go to AUTO
- AUTO (particle feed control active)
- Purge

When waiting to detect the presence of particles (just one will do), the system starts with a manual output of 13 % (in manual the vibration amplitude controller is active). While no particles are detected, the feeder is ramped up gradually at a rate of 2% every 10 seconds. Once an output of 30 % is exceeded the ramp-up rate becomes 5 % every 10 seconds until 60 % output is achieved. After 60 % output is reached the ramp up rate becomes 8 % every 10 seconds until the output exceeds 90 % output. If a particle is detected at any point while ramping up, the output is immediately set back to 13 % and the next state entered (waiting for enough particles to go to AUTO).

If no particles are detected, and the sequence has not yet been in AUTO when 90 % output is exceeded then there is a fault of some sort. Either there was no material in the bin/feeder at all, or there is an optical sensor fault and it is not detecting the particles. If no particles are detected, and the sequence was previously in AUTO, then the system is deemed to be clear of material and the processing of the batch is complete.

When waiting for enough particles to go to AUTO, the system is ramped up in the identical fashion while waiting to detect a particle until a preset particle count is detected. 8 particles per PLC cycle (100 ms) is currently being used, and corresponds to a setpoint of 8%. Once the preset particle count is detected the system moves into the AUTO state. The ramp-up sequence is also responsible for purging the system at the end of the cycle when there is insufficient material present to go back into the AUTO state. When no more material is detected at 90 % the processing of the batch is complete.

7. CONCLUSION

Despite attempts to 'derail' the controller (e.g. intentionally holding the particles up in the feed tray), it worked suitably in the test facility. There are a number of conditions that must be achieved in order to ensure repeatable performance:

1. Ensure that the spring configuration on the feeder is according to specification for the application. Modifying the springs can drastically change feeder performance so that the controller is no longer able to function.
2. The feeder controller module must be set up using an rms voltmeter. The feeder must be connected, with an empty or pre-loaded feeder tray in place. It is also suggested that a graphical indicator, or hand-held vibration calibrator be present on the feeder tray to confirm the displacement range (this is an invaluable tool). This is often useful, since although the voltage delivered by the controller module is correct, mechanical interference at interfaces often damps the vibration so that the desired displacement is not achieved.
3. The vibration transmitter must be either in its factory calibrated state, or must have been calibrated on a test bench.
4. If alternate vibration transmitters are used it is important to note the measurement units. Vibration transmitters use g, g rms, rms displacement, or peak-to-peak displacement. The differences in output imply a difference in the gain that the vibration controller will see and the controller parameters must be changed accordingly.
5. If the hardware calibrations have been carried out it should not be necessary to change the vibration amplitude controller parameters.
6. The optical detector should be set for the minimum pulse width, and for the maximum possible sensitivity. The sensitivity may need adjustment, depending on how much vibration is present in the system at 100 % output. If the counter card detects any particle counts at this time then the sensitivity must be reduced. The detector should also be checked visually, since it was noted that there were times when it would trigger in the presence of dust.
7. It should not be necessary to modify the controller parameters for the particle feed controller once they have been checked on site.
8. Increasing the particle feed controller gain destabilises the system, since the system response cannot be speeded up much more compared to the filter time constant.
9. The controller and filter parameters have been set up in such a way that variation in equipment parameters will not have a significant impact on the system behaviour.
10. Plant personnel are often tempted to increase particle feed controller gain in an attempt to speed up the batch processing time. Aside from making the controller unstable, this impacts negatively on downstream processes since they no longer receive their design feed, and is a totally counter-productive exercise. It is preferable to increase the capacity of a system if the batch processing is not fast enough (i.e. use a larger feeder, or add another feed module).

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