Setting PID Parameters and Notch Filters Using Black's Diagram

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Abstract

In recent years, nanopositioning systems have made a great deal of progress, in terms of both precision and speed. Despite the latest advances in automation, the PID corrector network is still of interest because it is easy to implement and use; all the more so since several automatic adjustment methods have appeared on the market. To boost the performance characteristics, however, it has become crucial to analyse and compensate the mechanical resonance frequencies. An approach using mathematical modelling is effective, but not easily accessible to users lacking the required knowledge.

The purpose of this article is to present an approach for the adjustment of PID parameters and notch filters. This method is based on a measurement of the real transfer function of the positioning stage. The transfer function of the open loop is obtained using the experimental results and the theoretical results of the corrector network (PID and notch filter), and this function is represented on Black's diagram.

1 Data acquisition

1.1 Experimental data

The precision of the adjustment will depend on the quality of the transfer function results. The stages that give a usable transfer function are those with a low level of friction and a position encoder with a high resolving power of the order of a nanometre. The excitation signal used is a pseudo-random binary sequence with a uniform spectrum over a broad frequency band, even at low frequency. It is sent directly to the power electronics. The transfer function is calculated between the encoder output and this excitation signal. The display of the coherence function allows the validity of the measurement to be confirmed. The measurement is taken in an open loop.

1.1 Theoretical data

Theoretical data are obtained by modelling the PID integrated in the controller. For greater precision, the use of the Z-transform is important to take the sampling time of the controller into account. The notch filters can also be modelled. This means that, for a set of PID and notch parameters, the transfer function of the corrector network can be calculated.

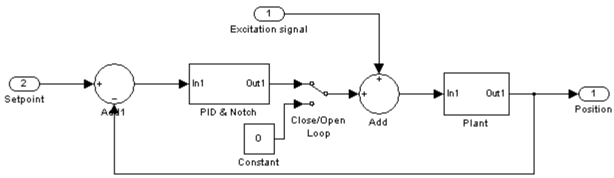


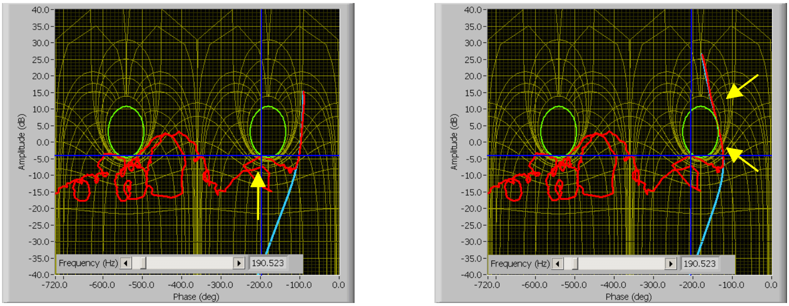
Figure 1: Block Diagram

When both transfer functions are known, the open-loop transfer function can be determined.

2 PID setting

The basic principle is to have maximum gain for the widest possible bandwidth. Stability control is applied using Black's diagram and by ensuring that the open-loop transfer function is tangential to a prior set iso-gain curve (3 dB by default). At first, the PID parameters are initialised to zero. The values of the parameters KD, KP, and KI are then increased, in that order, to make the transfer function tangential to the iso-gain curve.

For example, a mechanical system driven by a linear stage equipped with a rule with a 4-micrometre step and interpolated to 1 nanometre, with a linear motor, gives the following results (iso-gain curve set to 3 dB, KD = 360, KP = 80000, KI = 1E+6). With this setting, the crossover frequency is equal to 60 Hz.



Effect of the D term ***Effect of the PI terms***

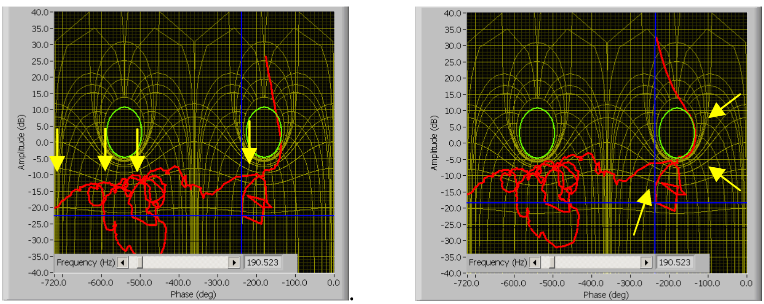
Figure 2: Black's Diagram with PID

For comparison, the blue curve is the transfer function obtained with a simplified model of the system (double integrator followed by a first order to model the bandwidth of the driver), neglecting the mechanical modes.

3 Notch filter setting

3.1 Attenuation of resonance frequencies

For the previous setting, the mechanical resonance frequencies prevented the PID gains from being increased. Notch filters are used to reduce the transfer function gain locally at the resonance frequencies. Their frequency is set to the mechanical resonance frequency and their gain is adjusted to flatten the resonance. The resonant frequency is determined by using sliders. Their width is set to control the attenuation locally (F1=190 Hz, B1=30 Hz, G1=0.1, F2=350 Hz, B2=100 Hz, G2=0.1,F3=490 Hz, B3=100 Hz, G3=0.1,F4=770 Hz, B4=500 Hz, G4=0.1).



Effect of notch filters ***Effect of PIDs***

Figure 3: Black's Diagram with PID and Notch

When the notch filters have been set, the PIDs must be adjusted again (KD = 600, KP = 100 000, KI = 1E+7). In our example, the use of notch filters gained us a factor of 50% on the crossover frequency (90 Hz) of the system, and multiplied the KI by 10.

3.2 Attenuation of low-frequency perturbations

Notch filters can also be used to attenuate the effect of perturbations by adding a gain locally at the frequency of the perturbations. The most frequent penalising perturbations are ground vibrations (10 to 20 Hz), movement of the table on which the stage is placed (1 Hz to 4 Hz, according to the insulation), and the step of the magnets in the linear motors, which create a perturbation at a constant frequency for a constant-speed displacement (1 Hz to 10 Hz). For these low frequencies, narrow-bandwidth notch filters (approximately 1 Hz) with gain greater than 1 will be used, and their effect on the stability will also be checked on the Black's diagram.

4 Conclusion

Unlike an adjustment based on a model, the setting of PID parameters from the measured transfer function makes it possible to take all mechanical modes into account. The adjustment method based on the use of Black’s diagram is easy to use because it is graphical and the end user does not need to perform any calculations, and all information (gain margin and phase margin) are present in a single graph. The iso-gain curve is used to delineate a robustness zone. The methodical and controlled adjustment of PID parameters and notch filters obtains the best possible performance characteristics in an efficient way.

References:

[1] "Stabilized Feedback Amplifiers" by H. S. Black published in *Bell System Technical Journal*, January 1934.