Advantages of Auto-tuning for Servo-motors

Executive summary

The same way that 20 years ago computer science introduced "plug and play," where devices would self-adjust to existing system hardware, industrial motion control now has similar capabilities with auto-tuning servo-drives. Auto-tuning identifies the optimal parameters of the controller, and the motor determines the type of load and type of mechanical coupling. This paper explains the foundational issues of control and tuning, discusses how auto-tuning suppresses oscillations and makes friction compensation, and provides a quantitative comparison of manual and auto-tuning in three common mechanical system schema.

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Introduction

The word of computer sciences facilitated user's life with the famous "Plug and Play". For over twenty years, it is no longer necessary to be a computer expert to take advantage of hardware.

Industrial facilities are becoming more and more complex, since they are required to provide high rates of production, while ensuring the longevity and reliability of equipment. That implies for motor command, an optimal setting tuning. But any company, as big as it is, does not necessarily have skills in motor control.

Today there are methods which are similar to the "Plug and Play" in the world of "Motion“: the Auto-tuning. This system, integrated in the Lexium 32 from Schneider Electric, makes the installation faster and easier. When the Auto-tuning is run, the servo-drive will automatically adjust its gains, by detecting the type of motor under control, but also the load in movement.

Issues of control and tuning

The basic structure of a control loop consists of sensors, a subtraction operator, and a controller.

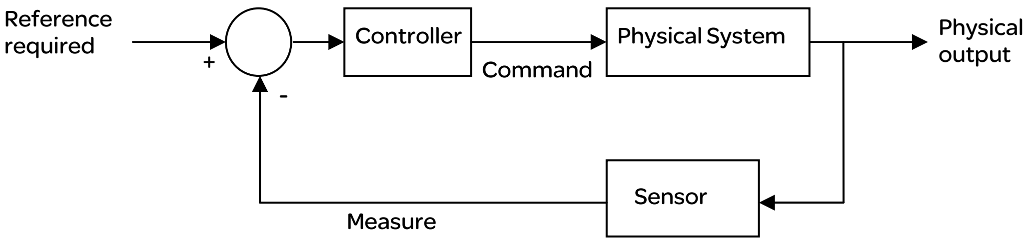


Figure 1: Closed Loop with a controller

The reference to compare the performance of a controller is often the step response. This kind of test is representative of most operations in an application. For example when a change of position is asked on a motor, a step of position is applied at the input (Reference required) and the output is observed (Physical output).
Depending on the mechanics which are controlled, the step response can be a first order response, a second order response or a mix of these responses. Some vocabulary is important to define a step response.

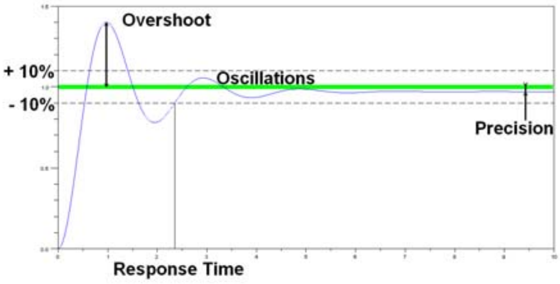


Figure 2: Typical step response for a second order system

Response Time: One of the most important parameters is the response time of the controlled system. It is often defined as the time which is necessary for the system to reach the reference with an error of 10%.

Overshoot: The response is temporarily over the reference. This phenomenon which is due to a small damping is called “overshoot”. Most of mechanic systems have this kind of phenomenon.

Oscillation: Due to an under-damped system, the response can oscillate during a define time.

Precision: The response can reach the reference with more or less precision, which is defined by the relative difference between the reference and the response final value.

Principle of auto-tuning

The tuning of the Lexium 32 offers three possibilities: the auto-tuning, the comfort-tuning and the expert-tuning.

Auto-tuning is an intelligent system, which seeks the optimum parameters of the controller. It does not require any knowledge from the user. The motor will perform a sequence of movements in order to determine the type of load that is controlled and the type of mechanical coupling. This tuning covers most industrial applications with good performance.

The comfort-tuning provides the ability to add additional requirements to the auto-tuning, if the user wants a particular type of response. This tuning does not require knowledge in the field of control.

The expert-tuning is a manual tuning for extreme applications. It allows even more requirements on the response but needs good knowledge in the field of control.

In the following of this document benefits of auto-tuning will be highlight.

Oscillations suppression filter

During the auto-tuning, filters are added to the controller to eliminate the oscillations due to resonances. Indeed, mechanical systems have resonance frequencies that disturb the control of the trajectories. The auto-tuning searches these frequencies and adds notch-filters to suppress them.
Figure 3 shows the response of a system after the auto-tuning, where the notch-filters are manually removed.

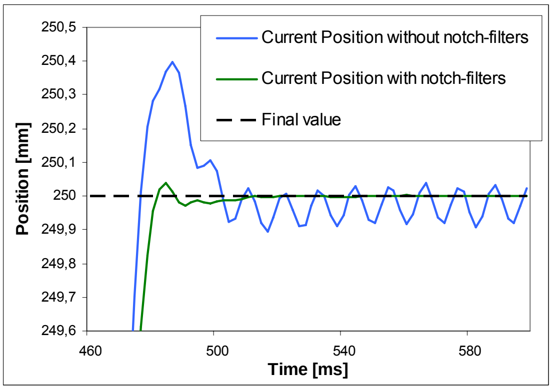


Figure 3: response of the linear spindle axis, with and without notch-filters

The difference is obvious; a frequency of 90 Hz is eliminated thanks to a notch-filter. This type of tool has two advantages. Firstly, it prevents the command from exiting frequencies that could damage the mechanical parts. Secondly, it speeds up the response time without making the system unstable.

Friction compensation

Mechanical movements inevitably cause friction effects. Auto-tuning evaluates this phenomenon and compensates it. This helps making the system more linear and more easily controllable. It also reduces tracking errors.
Figure 4 shows the response of a system after the auto-tuning, where the friction compensation is manually removed.

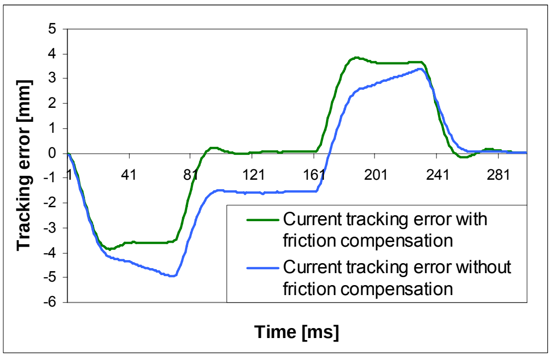


Figure 4: tracking error of the linear belt axis, with and without friction compensation

The response without friction compensation permanently delayed compared to the reference. This dynamic error is a tracking error. It could be a problem when the system must follow complex trajectories. The friction compensation cancels this tracking error systematically.

Mechanical systems to the test

Round table

Mechanical description

The round table (figure 5) consists of a motor coupled to a gearbox with a factor of 10:1, which is coupled to a metal disc. A mass of 1.5 [kg] is fixed on the disk (at a distance of 160 [mm] from the center of rotation). The control and measurements are performed by the motor encoder.

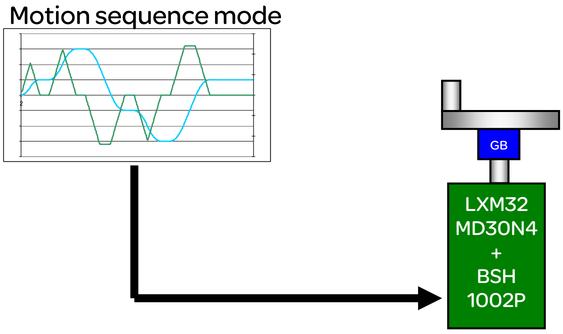


Figure 5: Round table schema

Test sequence description

The test sequence is a succession of angular position:

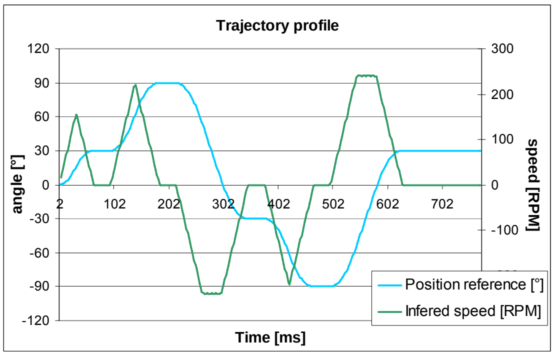


Figure 6: Round table sequence

The left scale represents the angular positions of the table, while the right scale represents the angular velocity of the table which is limited to 240 [RPM]. The objective is to reach the set-point without static error, with only one overshoot. The response time is defined here as the time which is necessary for the system to reach the set-point 1 0.05 [°], from the time the reference has reached the final value in the error window.

Linear spindle axis with motor encoder feedback

Mechanical description

The linear spindle axis (figure 7) consists of a motor directly coupled to a screw without gearbox. The screw moves a carriage, with a load of 25 [kg]. The control and measurements are performed by the motor encoder.

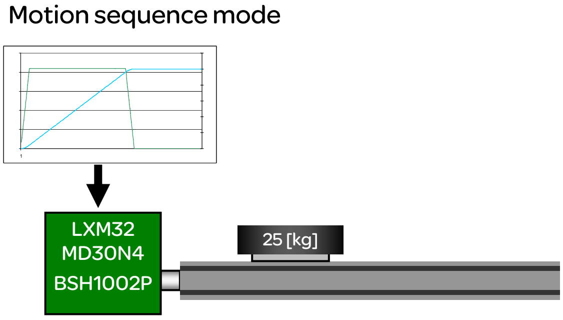


Figure 7: Linear spindle axis with motor encoder feedback schema

Test sequence description

The sequence performed for the tests is a shifting of 250 [mm], limited on speed with a maximum of 2100 [RPM]:

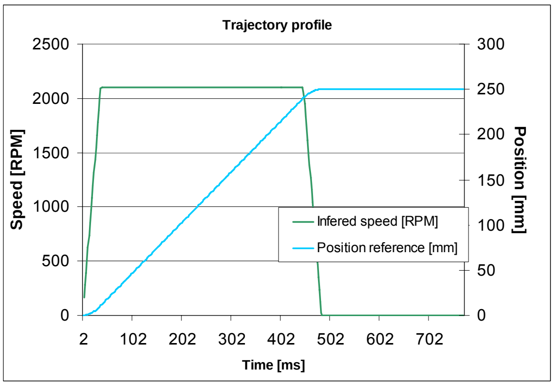


Figure 8: Linear spindle axis with motor encoder feedback sequence

The left scale represents the motor speed [RPM], while the right scale represents the position of the carriage in [mm]. The objective is to reach the set-point without static error, with only one overshoot. The response time is here defined as the time which is necessary for the system to reach the set-point 1 0.05 [mm], from the time the reference has reached 250 [mm] in the error window.

Mechanical systems to the test

Linear belt axis with machine encoder feedback

Mechanical description

The linear belt axis (figure 9) consists of a motor directly coupled to the belt without gearbox. The belt moves a carriage bearing only its own weight. The control and measurements are performed by the machine encoder to provide more precision in this type of elastic coupling.

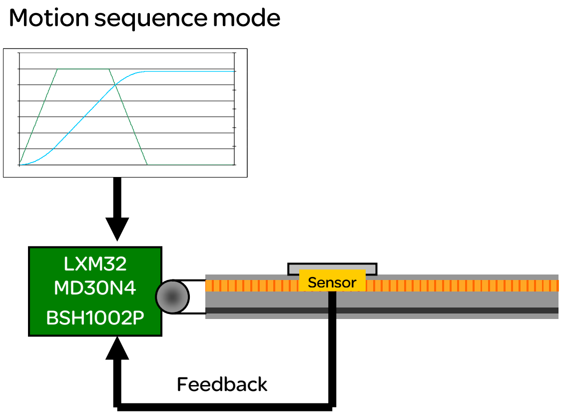


Figure 9: Linear belt axis with machine encoder feedback schema

Test sequence description

The sequence performed for the tests is a shifting of 500 [mm], limited on speed with a maximum of 1200 [RPM]:

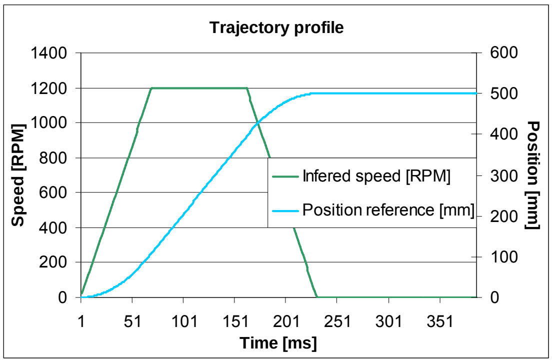


Figure 10: Linear belt axis with machine encoder feedback sequence

The left scale represents the motor speed [RPM], while the right scale represents the position of the carriage in [mm]. The objective is to reach the set-point without static error, with only one overshoot. The response time is here defined as the time which is necessary for the system to reach the set-point 1 0.1 [mm], from the time the reference has reached 500 [mm] in the error window.

Time for the tuning adjustment

A major advantage of auto-tuning is the time which is necessary to adjust parameters of the controller. The following table summarizes the adjustment time necessary for the auto-tuning (in green) compared with the adjustment time for the expert-tuning (in blue).

System	Time for the tuning adjustment [min]
Round table	1
	240
Linear spindle axis with motor encoder feedback	1
	75
Linear belt axis with machine encoder feedback	1
	45

Typical applications

The amount of time saved by the auto-tuning is more significant when an application includes several axes. Systems presented in this section are typical applications, where the amount of time saved by the auto-tuning is estimated.

Bottle inspection:

Bottles arrive on a treadmill and are carried on the round table. Each bottle is inspected by a sensor that moves down and up. The bottles inspected are then released on another treadmill. Because of the speed of inspection, the sensor is coupled to a linear belt axis.

Figure 11: bottle inspection schema

This system consists of two motors, one for the turntable, and the second for movement of the sensor. Assuming that the adjustment of each axis is performed by an auto-tuning rather than an expert-tuning, the time saved is considerable:

Estimated time saved ▶ 4h45

Pick & Place:

A three-dimensional portal grabs objects to place them onto a support. The object is grasped by pliers. The pressure is controlled to avoid any damage on the object in movement. The three axes are linear belt systems, while the pliers are directly coupled to the motor.

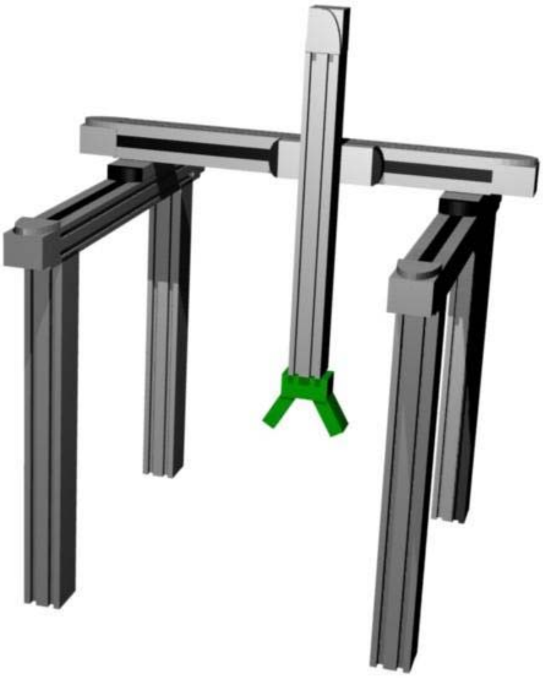


Figure 12: Pick and place schema

This system consists of four motors, three for the linear belt axes, and one for the pliers.

Estimated time saved ▶ 2h15

Time for the tuning adjustment

2D welding table:

A two-dimensional table drives a welding equipment in order to assemble sheet metal. The plates are clamped by mobile anchorage. For the regularity of the weld, the table is made of linear spindle axis. It is the same for anchors that require precise positioning.

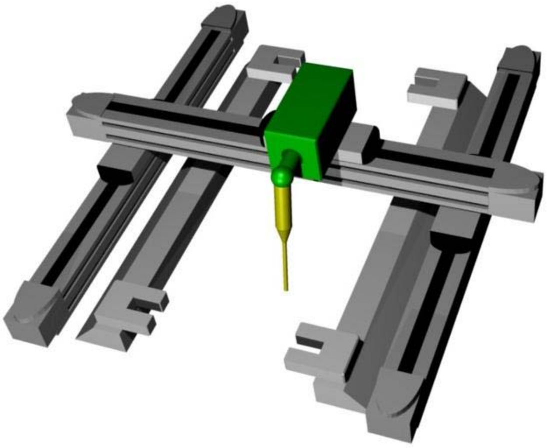


Figure 13: 2D welding table schema

This system consists of four motors which must be controlled.

Estimated time saved	► 5h

Response analysis

To quantify the performance and the quality of the control, the response after an auto-tuning is compared with the response after the fastest expert-tuning obtained. The trajectories imposed are described in parts "Test sequence description". The type of response obtained is as follows:

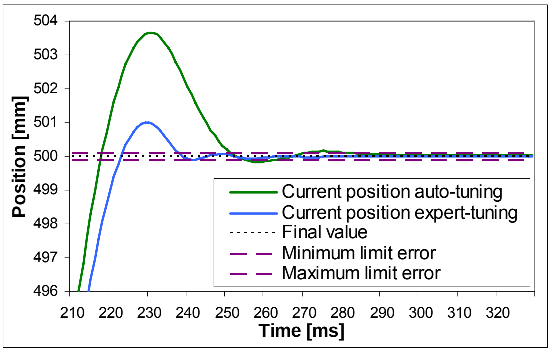


Figure 14: Response of the linear belt axis with machine encoder feedback

The mechanical wear also has to be considered, since if the expert-tuning is faster, it is also much more strain on the motor shaft and the coupled elements. The following figures show the stator currents, representing the torque applied to the shaft depending on the controller tuning. It is clear that with the auto-tuning, the command is softer.

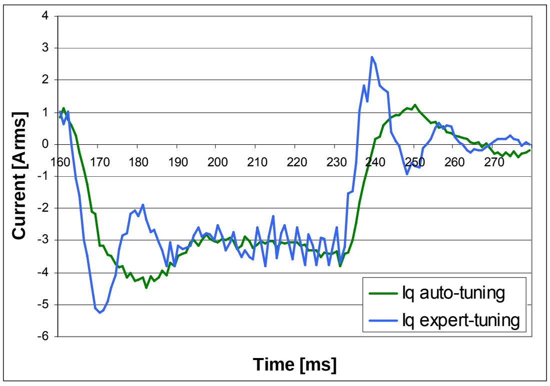


Figure 15: Current for the linear belt axis with machine encoder feedback

Performance

The results are summarized in the table below. Each system is represented with the results after an auto-tuning (in green) which are compared to those after an expert-tuning (in blue).

System	Response time [ms]	Overshoot [%]	Maximum tracking error
Round table (sequence from 30° to 90°)	14	1.295	1.146 [°]
	6	0.140	0.812 [°]
Linear spindle axis with motor encoder feedback	< 2	0.015	0.330 [mm]
	< 2	0	0.140 [mm]
Linear belt axis with machine encoder feedback	54	0.734	3.837 [mm]
	9	0.199	3.157 [mm]

Typical sequence

For a better understanding of the performance differences between the auto-tuning and expert-tuning, repetitive sequences are applied on each system. The principle is to make a back and forth, defined by two positions, as quickly as possible.

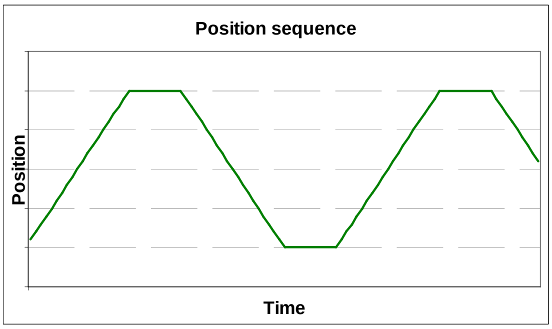


Figure 16: back and forth sequence

The rising time is determined by the sequence of previous tests, the stabilization time depends on the tuning (auto-tuning vs. expert-tuning). The number of back and forth possible during one minute is inferred.

Response analysis

Round table

The difference between two angles is 60 degrees. Once the position is reached, a delay of 10 [ms] is imposed to simulate an action.

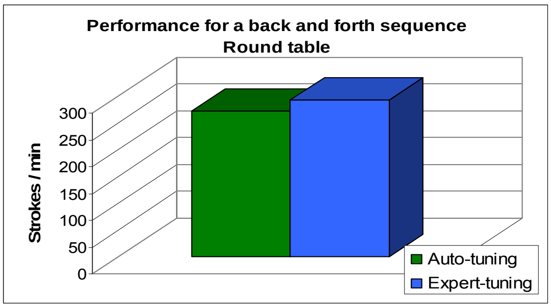


Figure 17: Round table performance

Linear spindle axis

The position to reach is 250 [mm]. Once the position is reached, a delay of 10 [ms] is imposed to simulate an action.

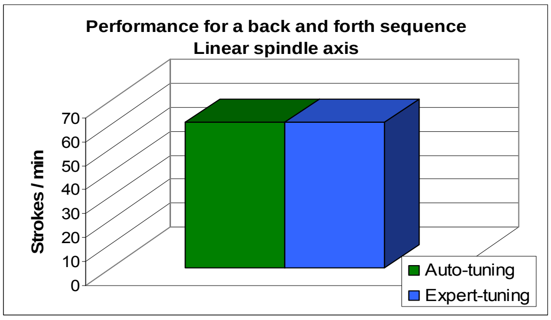


Figure 18: Linear spindle axis performance

Linear belt axis

The position to reach is 500 [mm]. Once the position is reached, a delay of 10 [ms] is imposed to simulate an action.

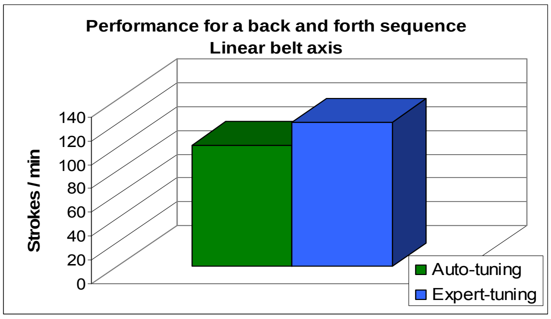


Figure 19: Linear belt axis performance

Conclusion on performance

Measures on a back and forth sequence shows that the time saved is not very important with an expert-tuning. The biggest difference is observed on the linear belt axis system, where the rate for the auto-tuning is about 102 [strokes / min], whereas the rate for an expert-tuning is about 121 [strokes / min]. For the linear spindle axis system the gain is null, since the stabilization time is the same whatever the tuning.

Longevity of mechanical elements

Because of the acceleration, we can infer a longevity index for the controlled systems. A more flexible command lengthens the life of the materials.

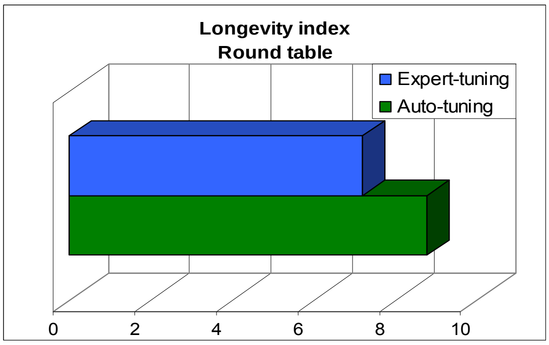


Figure 20: Round table longevity index

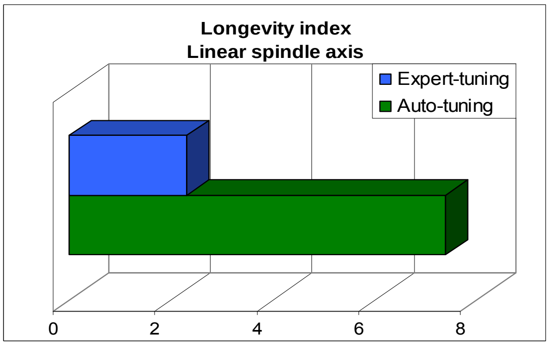


Figure 21: Linear spindle axis longevity index

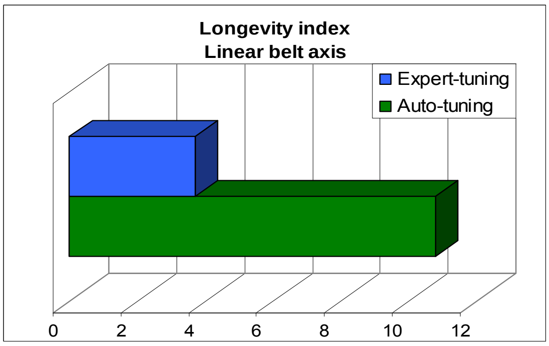


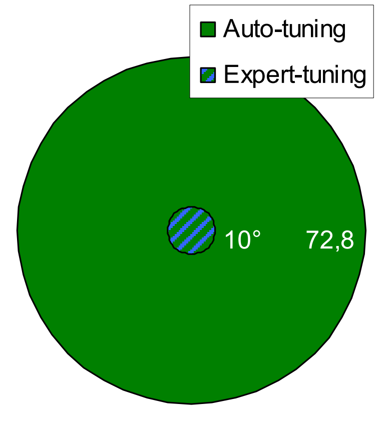
Figure 22: Linear belt axis longevity index

The difference is very visible on the linear axis systems since the longevity index is about one to three thanks to the auto-tuning. Auto-tuning is also more robust to variations of the system.

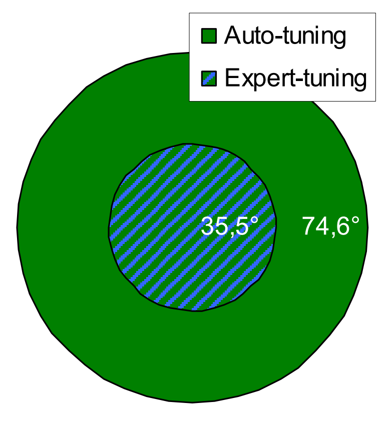
Theoretical study of robustness

The stability of a controller system is a crucial point when working conditions of the system change with time. This typically occurs when the load moved varies, or external actions disrupt the moving parts.
A controller is said robust if it is able to continue to operate stably, even in the presence of changes or disturbances. The simulation of the linear model of {motor + controller} allows estimating the robustness of the controllers observing the phase margin.

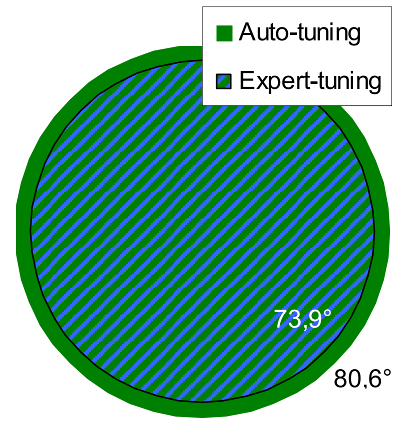
Phase margin : Round table



Phase margin : Linear spindle axis with motor encoder feedback



Phase margin : Linear belt axis with machine encoder feedback



By observing the phase margins, it is clear that auto-tuning is more robust because the margin is larger. A criterion often adopted is a phase margin larger than 45 °. In each system, the auto-tuning provides a phase margin above the norm.

Conclusion

Complex applications have no more difficulties in control. Thanks to the auto-tuning, the designer and the user of industrial machines can concentrate on the application, regardless of the tuning of their motors.

Auto-tuning provides efficient responses, suitable and viable for mechanics. The controller is robust and without tracking error. All of these advantages come without any knowledge in the field of control, and with a minimum time for tuning adjustment.