LOGISTICS

Reaching new heights

Working with industry and academic partners, ABB has been able to move beyond theoretical research results to introduce the first limited-version ACS880 drive control program with an anti-pendulum function for stacker crane customers. This new function minimizes mast oscillations and enhances stability, helping customers to reduce material cycling time.

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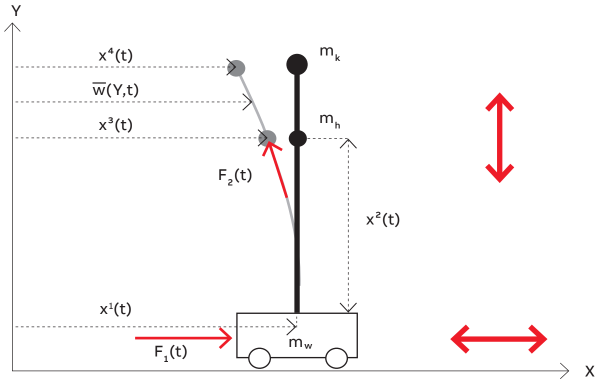
The materials handling industry typically uses stacker cranes to store and retrieve loads. This industry is under increasing pressure to fulfill economic and sustainability targets. Decreased material handling cycle times, demands for reduced costs and energy consumption require the use of ever taller and more lightweight cranes (less metal). These structurally less stiff cranes should position loads rapidly and precisely while maintaining workload stability and safety. Yet, such crane frame structures are flexible by nature; crane motion can result in harmful mast oscillations. The inertial force of acceleration or braking movement can reduce stability and derail positioning accuracy; compromising safety and possibly damaging the material being moved. Moreover, the dynamics of these machines

Decreased material handling cycle times, etc. require the use of ever taller and more light-weight cranes.



$$\rho A\ddot{w} = -EI\frac{\partial^4}{\partial Y^4}w,$$

$$m_w\ddot{x}^1 = F_1 - EI\frac{\partial^3}{\partial Y^3}w\Big|_0,$$

$$m_h\ddot{x}^2 = F_2 - m_h g - m_h x^3\frac{\partial}{\partial Y}w\Big|_{x^2},$$

$$m_h\ddot{x}^3 = EI\left(\frac{\partial^3}{\partial Y^3}w\Big|_{x^2_-} - \frac{\partial^3}{\partial Y^3}w\Big|_{x^2_+}\right)$$

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depends on the lifted load, which varies with the magnitude and position. To circumvent the damaging consequences of oscillations, the crane's operating system requires a few seconds to stabilize so that vibrations can cease before movement can continue. This process is time-consuming and as such reduces throughput and performance.

How then can drive control applications minimize stacker crane mast oscillations while incorporating quick, accurate and robust control at minimal cost, and improve throughput? ABB's answer to this challenge is incorporating an anti-pendulum function option based on ABB's ACS880 Position control program.

A dependable partner

With sustainability and performance paramount, stacker crane manufacturers know they can depend on ABB to provide control strategies to fit their logistical needs and meet environmental and economic goals. ABB introduced ACSM1 motion control drives in 2007. These flexible and versatile drives provide general speed and torque as well as versatile motion control features. Used to control induction, synchronous and asynchronous servo- and high torque motors with various feedback devices, these drives are used by stacker crane customers. Building on innovation, ABB introduced the ACS880 Position control program as a successor to the classic ACSM1 motion control drives for stacker crane customers in 2018 – with absolute and relative positioning, profiled positioning, position synchronizing and fast position latching. Nonetheless, small scale crane manufacturers have yet to develop an anti-pendulum function. Enter ABB to provide these customers with an anti-pendulum solution to minimize mast oscillations, accurately and rapidly.

How it all began and establishing a path

Understanding the important connection between collaboration and innovation to achieve the full potential of their drive control solutions, ABB works closely with their business and academic partners. In early 2017, ABB began a collaborative investigation to determine the feasibility of including an anti-pendulum function and functional safety (and additional base control features) in their ACS880 Position control program for stacker cranes. Having relied on an ACSM1 motion control drive for stacker crane control for over a decade, one of ABB's customers sought a solution to an expanding challenge: achieve higher throughput economically and sustainably in ever taller warehouses, yet avoid mast oscillations in a 68-ton 32 m tall stacker crane that must lift and shift 6-ton loads.

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Stacker crane manufacturers know that ABB will provide control strategies to fit their logistical needs.

ABB joined forces with the University of Linz, Austria (JKU) to investigate such an

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01 A mathematical model of a stacker crane developed by JKU. The forces acting on the crane (F), the mass of the lifting unit m_h, the mass of the tip m_k (used in JKU TB) and the mass of the driving unit m_ω.

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02 Schematic of the trajectory generation and motion profiles shown form the basis for the ABB's design.

02a Schematic of the control law for the driving unit: P-PI cascade. Shown is the trajectory generation used for transferring the lifting unit of the ABB SC from an initial-rest position to a target position.

02b SC anti-sway control motion profile simulation results of the advanced trajecory generation. Results from the standard motion control (left) and advanced control with the dynamic model (right). The proposed trajectory generation almost completely eliminates mast oscillations.

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In 2017, ABB began exploring an anti-pendulum function for ACS880 Position control program.

anti-pendulum solution. With theoretical-, testing- and design phases critical, an intense partnership evolved with each partner doing what they do best. And, because there is usually a gap between what is theoretically possible and what is practically viable, ABB expanded the preliminary results through tests and design iterations, turning them into tangible benefits that are manifested in a new ACS880 Program control anti-pendulum function.

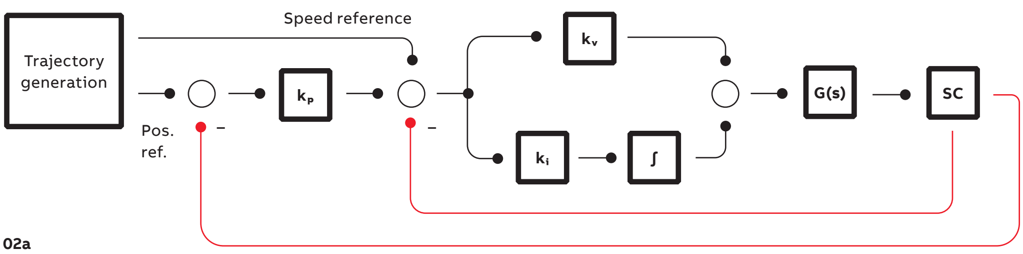
The research projects: an introduction
Having established a collaborative synergy between ABB and JKU, the parallel research projects focused on:

- Developing mathematical models to capture the dynamics of single mast stacker cranes: the JKU test bench (TB), small-scale demonstrator model, and ABB's stacker crane (ABB SC).
- Calibrating the generic model by identifying the parameters of the specific cranes in question.
- Creating a control scheme to generate the position and reference speed for the crane so that it does not oscillate during motion.
- Determining a feedback system so that residual oscillations due to model imperfections or external disturbances are cancelled.

Theoretical basis: mathematical models
To determine the feasibility of creating an anti-pendulum control function, flatness-based trajectory generation approaches were applied to ABB stacker cranes [1,2,3]. Test crane dynamics of both the ABB SC and JKU TB were modeled as a mixed-dimensional system that included partial differential equations (PDEs), ordinary differential equations (ODEs) and consideration of boundary conditions.

In each case, the PDEs are discretized by employing the Rayleigh-Ritz Method so that a pure ODE system is achieved to facilitate ease of system analysis and controller design at a later stage.

Nevertheless, the Rayleigh-Ritz discretization requires the choice of an ansatz function; the



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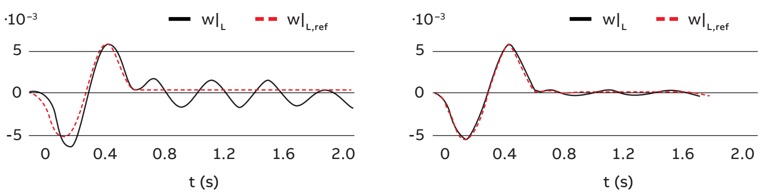

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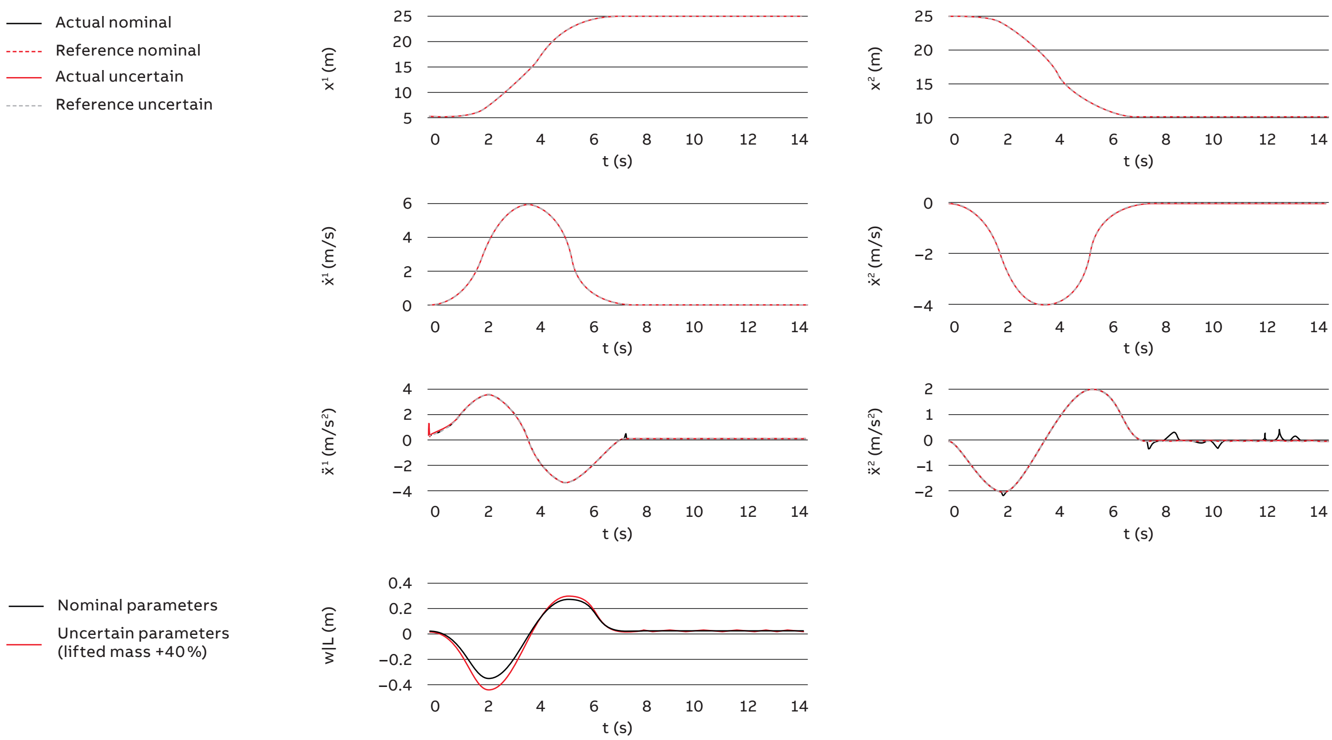

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structure of which is crucial. Once this function was chosen, the unknown system parameters were determined based on the boundary conditions. Specifically, the equations of motion were derived extending the Hamilton principle to the Lagrangian action functional, which yielded a mixed-dimensional system.

Significantly, in order to obtain equations of a finite-dimensional character, experts applied the Rayleigh-Ritz method (discretization): $\overline{w} = x^1 + \Phi_1(Y)\cdot\overline{q}^1(t)$ where, $\overline{w}(Y, t)$ is the absolute position of the beam as a function of height *Y* and time *t*, x^1 is the horizontal position of the driving unit, $\phi_1(Y)$ is the ansatz function (only a function of height *Y*) and, $\overline{q}^1(t)$ is the generalized coordinate (only a function of time). Here, it is notable that $\overline{w}$ is a function of (spatial) height and time, the individual components ϕ_1 and $\overline{q}$ are functions of one dimension only.

The all important ansatz function was determined according to:

$$\Phi_1(Y) = A_1\cdot\sin(\gamma Y) + B_1\cdot\cos(\gamma Y) + C_1\cdot\sinh(\gamma Y) + D_1\cdot\cosh(\gamma Y)$$

By substituting this equation as well as the ansatz function derived earlier, into the boundary conditions; and deriving the parameters *A, B, C, D, γ* by solving the resulting non-linear system of equations, ABB and JKU could obtain a sound model of the ABB SC →01.

Model calibration: identifying parameters
The sound theoretical model serves as a blueprint for describing the dynamics of stacker cranes. Nonetheless, for the practical application of the model to a specific stacker crane model, parameters must be identified. These unknown

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Working with JKU, ABB developed mathematical models to capture the dynamics of single mast stacker cranes.

parameters were calibrated: flexural rigidity, *EI*, density of the mast, ρA and mast damping coefficient, d_m.

Using measurement data from a real-world stacker crane fitted with a ACSM1 motion control drive, ABB could derive system parameters. Accelerating the drive unit so that the crane travels at constant speed without oscillating;

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03 Results for ABB trajectories as part of the robustification investigations. The ABB trajectories were applied to the JKU TB, which relied on measurement data. Here, a damping injection control law was added to suppress oscillations. Robustness simulation results: m_h, uncertain = $1.4 \cdot m_h$.

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04 A depiction of the input shaping used for the profile generation and its basis are shown.

04a Block diagram of the designed 3-step input shaper used for profile generation. Note, profile generation is given by speed reference specified by formula v(t) or as used here as 1D lookup table. Three branches of speed reference, which are shifted in time and scaled by a factor are used. Position reference is derived from integration of the speed reference used.

04b A schematic that illustrates the working principle of input shaping, which uses an initial and a delayed output at time to an oscillating system. As both inputs have the same amplitude (assuming there is no effective damping), the second input will eliminate the oscillation from the first signal and the system will move in a positive direction without oscillation.

then abruptly stopping the system, results in mast oscillations. The lifting unit is moved to two different positions (heights). Once the main oscillation frequency and its exponential decay was determined, a system of nonlinear equations relating the oscillation frequencies and damping ratios to the parameters EI, ρA and d_m, were solved. Parameters were then applied to a third height as a control.

Having identified mast and drive parameters of the ABB SC, the resultant calibrated dynamic models were then directly used for drive control development.

Trajectory tracking and robustness studies
To ensure that oscillation is minimized during crane motion, ABB developed control schemes to generate position and reference speed for the cranes.

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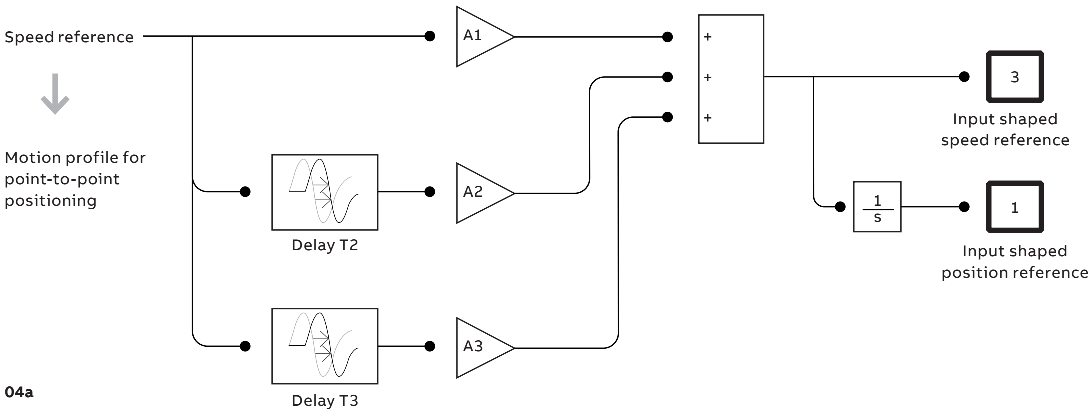
ABB's control system superbly and robustly positions the stacker crane with minimal residual oscillation.

Using polynomials to parameterize all system variables by means of flat outputs and derivatives, ABB's resulting equations similar to [3], depend on the flat outputs and their time derivatives; these were implemented in the trajectory generator →02a.

Here, a well-tuned P-PI cascade tracking the references generated by the flatness-based trajectory planner works well if no external



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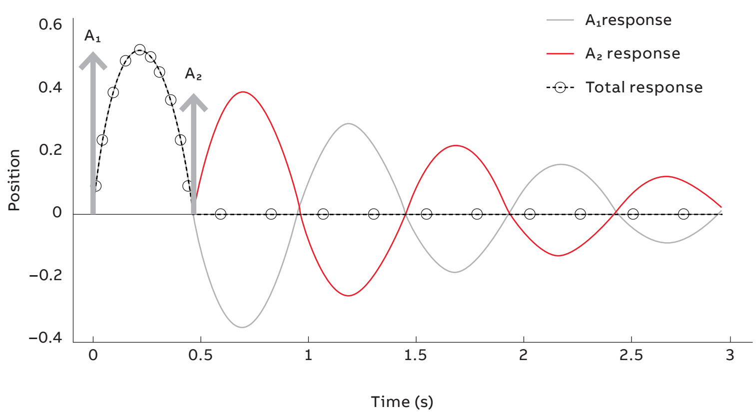

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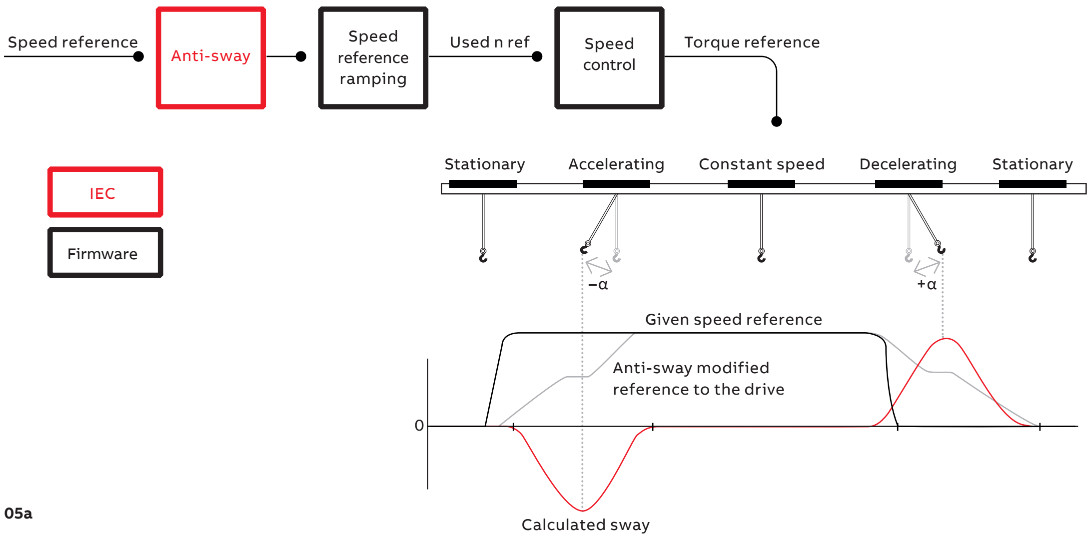

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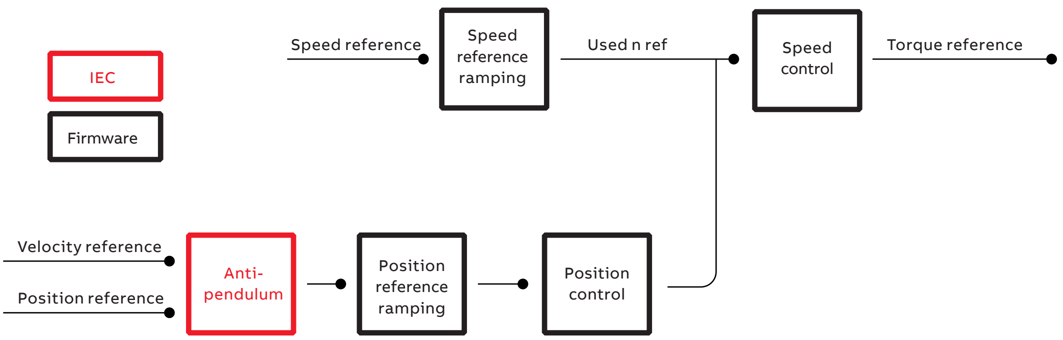

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disturbances are present →02b. To mitigate mast oscillations, in case of such disturbances, the cascade was extended with integrated feedback in the driving unit by means of a damping-injection control law [5,6].

By considering lifting-unit mass and beam parameters as uncertain quantities (although they were known) robustness was determined. The result is an amazingly robust system in both the JKU TB and the ABB SC cases →03. Critically, only major system parameter deviations impacted beam oscillations in the JKU TB; slight differences in lifting mass (+/- 10 percent) had almost no impact on the ABB SC; these are excellent results.

Translating theory into design

ABB strives for the best performing and economical control systems for their customers; this means using the most promising results. Therefore, ABB used the verified modeling →01 and the motion control results →03, as a basis, to develop an anti-pendulum control function that is easy to engineer yet delivers excellent performance and reliability.

ABB's new control method for point-to-point positioning of the stacker crane includes an input shaper →04a, trajectory planning, with the existing control chain of the ACS880 Position control program (motion profile generator, position controller and speed controller) [7,8].

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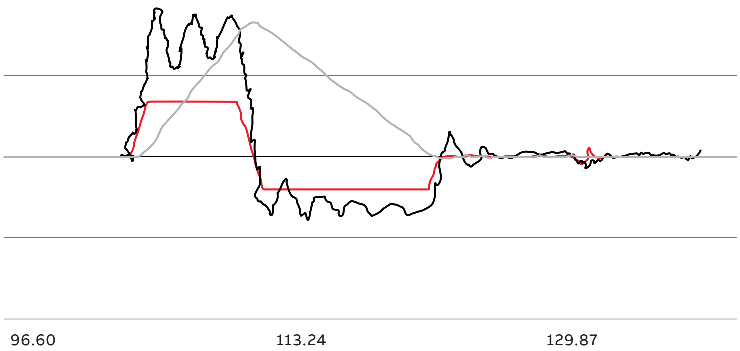
Customers can now accurately move loads, rapidly and affordably in the tallest of warehouses.

Input shapers are designed so that a created command signal tends to cancel its own vibration, reducing the residual swaying of the



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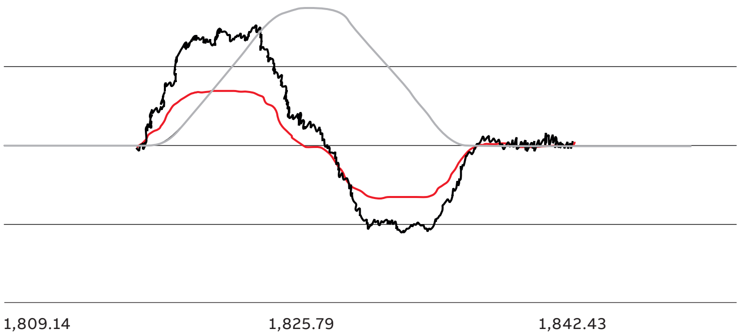

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05 Control schemes are illustrated.

05a ACS880 anti-sway crane control program (for EOT cranes)+N5050 scheme is illustrated in which the reference input changes are divided into two segments where the second is delayed in relation to oscillation cycle time.

05b ACS880 anti-pendulum position control scheme for stacker cranes is similar to the crane control scheme except that the division is into three segments instead of two. This is more robust against oscillation time error.

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06 Motion profiles generated that illustrate the impact of enabling the anti-pendulum functionality. The black line: 01.10 Motor torque, grey: 86.03 Actual speed, and red: 88.07 is estimated acceleration.

06a Motion profile generated by a basic jerk-limited motion without anti-pendulum functionality.

06b Motion profile generated once the three-step oscillation damping mode is enabled with anti-pendulum functionality.

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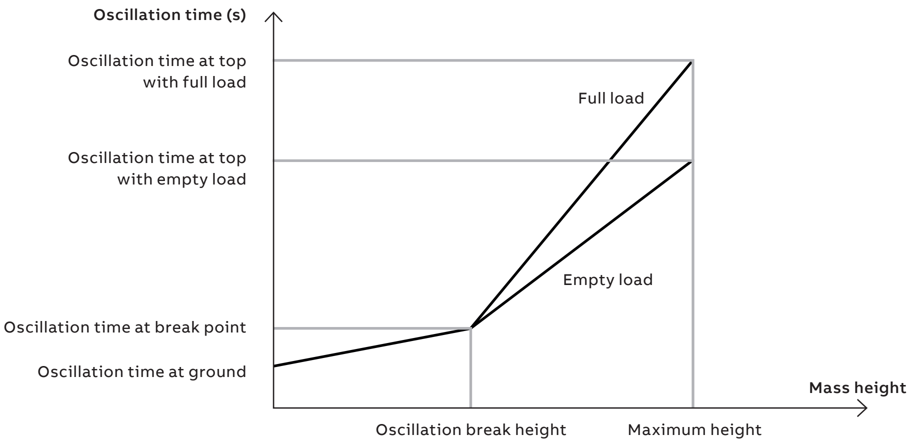
07 Oscillation swing time curves of empty and full loads based on crane target height. Below oscillation break height, mass of the load is not considered to impact the oscillation swing time; above the oscillation break height the mass of the load will have a proportional effect on the oscillation swing time.

structure →05a [7]. To achieve this, the damping ratio and the system oscillation, with different heights of the lifting unit (determined based on the dominant resonance frequency), must be known. Here, new system parameters can be obtained during system identification procedures when commissioning the ACS880 drive – a direct benefit to customers.

Because input shaping and damping injection (which dampens the existing residual swaying once the crane has reached its target position) yielded good results, demonstrating excellent performance even when only one function was enabled [7], ABB's experts included only input shaping (with a three-step input shaper) in the final anti-pendulum control function, which is currently available →04–05 [8].

Once the motion profile generator was selected and modified, ABB could design, and successfully implement the system identification procedures



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for storing and obtaining the needed system parameters ie, damping ratio and swing time.

In this way, ABB's designed control system superbly and robustly positions the stacker crane with the desired dynamics and minimal residual oscillation.

ACS880 Position control anti-pendulum function
Achieving a practical, yet economical, anti-pendulum function with excellent performance was ABB's goal from the onset. By designing a control function with a precise dynamic model of a stacker crane, an accurate calculation of motion is now possible →05b; ABB's resultant ACS880

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By reducing the time required to stabilize the structure from approximately 3.0 s to 0.25 s, material cycling times can be significantly reduced.

Position control program firmware (+N5700) in a special version with the anti-pendulum function is the culmination of these goals [8]. System stabilization is now possible in as little as 0.25 s.

Here, the standard position reference profile is modified so that it suppresses oscillations initiated by the motion profile itself to a load, acting as an oscillating mass →06. Pendulum suppression performance relies on the calculated system oscillation swing time, the time between two successive peaks of a decaying vibration, calculated for every operating point by the system based on curves (for every mass and height of the load) →07, additional parameters that the user must set, and the damping ratio, a constant given by the user. With the damping ratio ζ calculated using logarithmic decrement:

$$\zeta = \frac{In \frac{A1}{A2}}{2\pi}$$

where *A1* and *A2* are the vibration amplitudes at two successive peaks of the decaying vibration; and the other parameters easily obtained or applied, ABB's stacker crane customers will now be able to minimize unwanted oscillations for every storage floor and load encountered.

Delivering viable products
Following the commissioning of the first ACS880 Position control program for stacker cranes in spring of 2019, ABB implemented the anti-pendulum function proto-type. Successfully field-tested at an end-customer site in summer 2020, the first product-level limited-version ACS880 drive control program with an anti-pendulum function was commissioned and released with customized software for a stacker crane customer in early 2021. A new version that targets ABB's general stacker crane customers is currently being developed and is scheduled for release in 2022.

Thanks to the close collaboration with industry and academia, ABB has been able to provide stacker crane customers with an ACS880 Position control program with an anti-pendulum function that fits their needs. Stacker crane systems can now accurately move loads more rapidly and therefore more affordably without fear of oscillations, even in the tallest of warehouses →08. By reducing the time required to stabilize the structure from approximately 3.0 s to 0.25 s, material cycling times can be significantly reduced.

Moving beyond theoretical results to include tests and design iterations, ABB turns ideas into tangible innovative products. This is one way that ABB helps customers handle demanding logistic activity to better meet challenging economic and sustainability targets so important in today's competitive business environment. •

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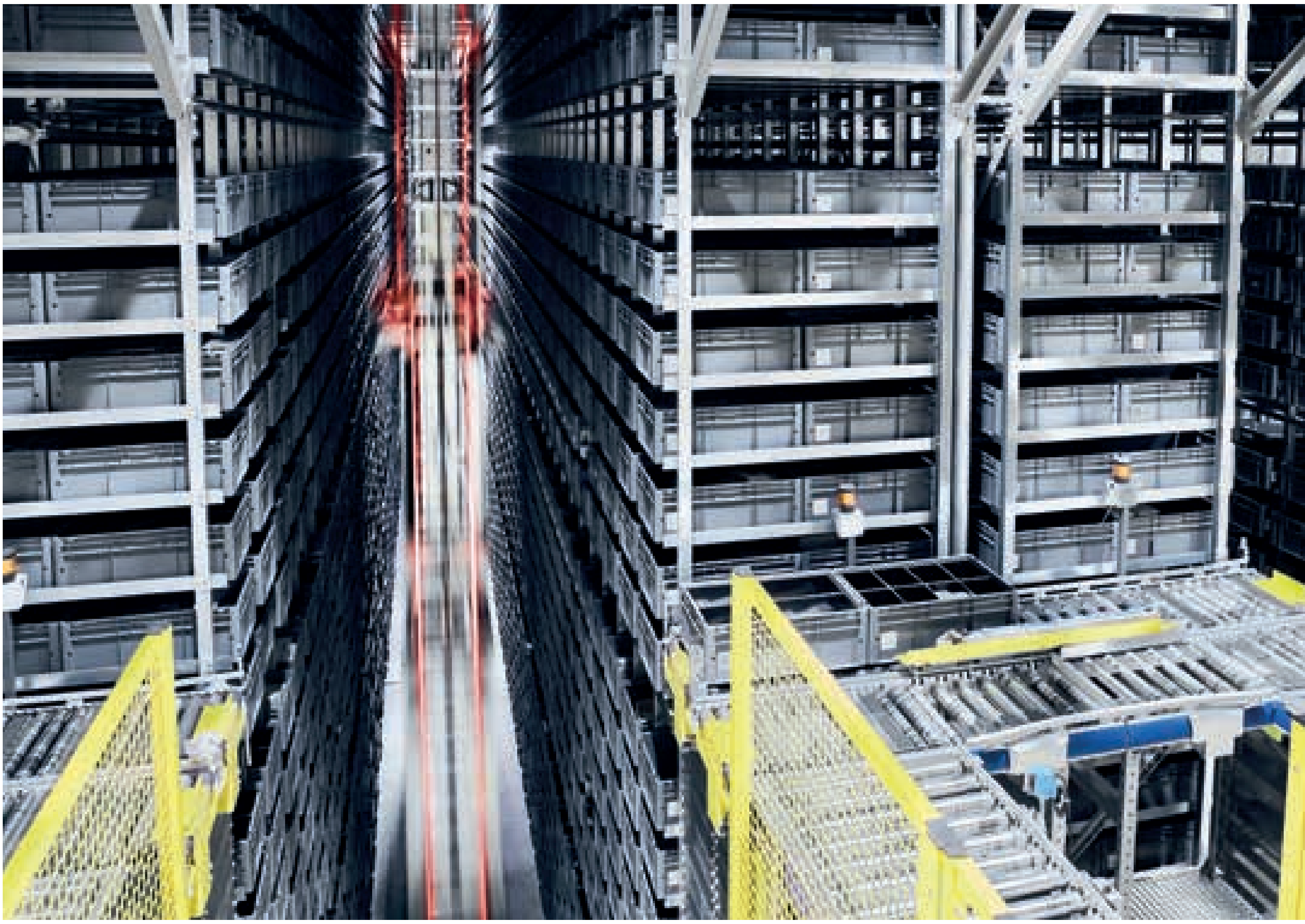

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08 With pressure to decrease material handling cycle times in ever taller warehouses, Stacker crane customers now they can depend on ABB to provide innovative viable solutions, such as the anti-pendulum function, to meet their demanding logistics needs.

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