Experimental Investigation of Hybrid Force and Position Control on an Electromechanical Feed Axis

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***Abstract*—In the area of production engineering, there are several ongoing efforts to improve manufacturing strategies and processes in terms of stability, quality, and efficiency. Control of process forces is one such appropriate measure for ensuring stable process conditions. This can also ensure reducing the number of parts rejected due to bad quality and thus aiding as a significant economic benefit. However, control of process forces in production machines with electromechanical feed axes is still a developing field and offers space for potential improvement. Control concepts at the process level, which enable a combination of force control and position control still need to be developed. The concept of hybrid force and position control is presented in this article as a possible approach. The implementation and practical testing on an electromechanical feed axis with a modern industrial motion control are described. For the combination of force control and position control, both controllers are integrated into the cascaded servo control at the same level. The controller prioritization and transition is realized with a weighting function, which is supplemented by a confidence interval. The parameterization of the control and the definition of the confidence interval are explained. In addition, various influencing factors are examined and their effects evaluated. The potential and advantages of the concept are elucidated.**

***Index Terms*—electromechanical feed axis, motion control, force control, position control, controller design, controller performance**

I. Introduction

Currently, the production technology is subjected to the influence of global markets more than ever and is forced towards high productivity and economy. A trend towards smaller batch sizes and more individual products is currently being established without compromising on the quality requirements, process reliability, and life cycle costs [1]. This leads to new challenges for the industry and hence resulting in promoting the development of flexible and adaptable machines and processes. In modern production machines, mainly electro-mechanical feed axes are used for motion generation. There are many strategies for controlling machine-specific quantities, such as the position or speed of electromechanical axes. The concept of cascade structure, also known as servo control, has already been established in this field [2]. However, the performance of this conventional control concept at the machine level has been exhausted. It cannot meet the ongoing efforts to further improve the manufacturing strategies and processes in terms of stability, quality, and efficiency. Control of process-specific quantities such as the process force is suitable to improve efficiency as well as the quality of finished parts and in turn resulting in significant economic benefits at this point. The force is often the limiting factor for the design of the processes and the choice of parameters. As a controlled variable, it is predestined to ensure stability and safety of many processes [3], [4]. Several force control concepts and algorithms have been developed and applied for numerous cases in production machines with electromechanical feed axes [5]. However, there are many challenges and requirements associated resulting in to a clear need for action in the future. While the control of process forces has considerable potential for improvement, position control is essential in many applications and processes for compliance with defined position specifications. Thus, the drafting of sophisticated control concepts, which enable joint use or the combination of force and position control, is neccessary. For production machines with electromechanical feed axes, the expansion of the cascaded position control with a force control offers a promising approach. In [6], the conventional position servo loop was augmented with explicit force feedback control for double-sided incremental forming. The force control loop is superimposed to the position control here. A similar control architecture was investigated for a burnishing process in [7]. The superimposed contact force control loop transmits a position offset value to the servo control. However, the outer control loops in a cascaded scheme react much slower than the inner ones. The force control is calculated here in the interpolation cycle (twofold servo cycle), so that the superposition has an adverse effect on the performance.

This publication focuses on implementation and practical testing of a hybrid concept for the combination of force control and position control on an electromechanical feed axis with a modern industrial

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motion control. Both controllers are integrated into the cascaded servo control at the same level. The controller prioritization and transition are realized in the motion control with a weighting function, which is supplemented by a confidence interval. Based on experiments, various influencing factors are examined and the potential of the concept is clarified.

The paper is structured as follows. In chapter two, the basic concept and the preliminary investigations are initially explained. This is followed by a description of the test setup and the implementation of the hybrid control concept together with confidence interval and weighting function. The experiments and results are presented in chapter four. Finally, there is a summary and conclusion.

II. Hybrid Control Concept and Simulative Preliminary Examinations

The hybrid control concept should make it possible to change between force and position control or use them both simultaneously. For example, this can be achieved by introducing a weighting function that prioritizes the controllers and their manipulated variables. The basic structure and functionality of this concept are illustrated in Fig. 1. This concept was introduced for a test rig with two coupled electromechanical feed axes and a control system from Siemens in [8]. The switchover between force and position control has already been implemented and the basic functionality was proven. A similar concept was proposed for hydraulic actuators by Pasolli and Ruderman [9]. Here, the hybrid position and force control was realized with event-based switching between both control modes. The transferability of the concept with two coupled electromechanical feed axes to a single axis and a control system from Beckhoff was proven in [10].

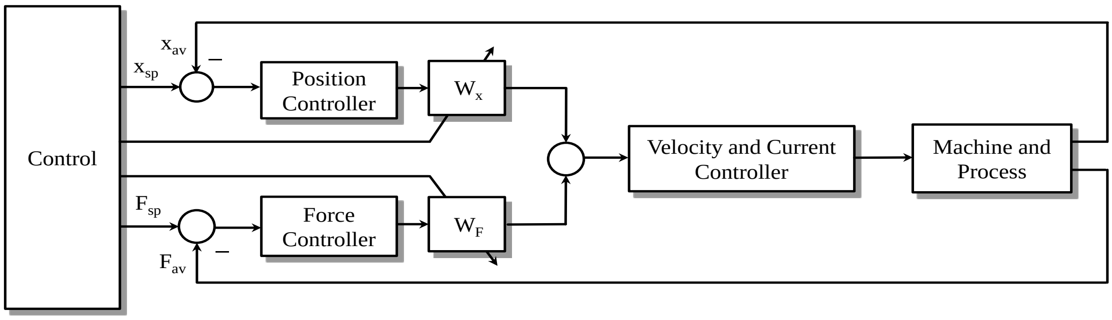

Figure 1. Concept and structure of hybrid force and position control

The design and performance analysis of the force controller as well as the behavior of the switchover with an electromechanical feed axis for a force-controlled process were investigated. Moreover, empirical setting factors and general adjustment rules were evaluated with regard to their suitability. It has been found here that good results can be achieved with the symmetrical optimum. In addition, the functionality of the switchover has been demonstrated experimentally. The effects of the hybrid concept with simultaneous utilization of both controllers and a weighting function were examined by simulation in [11]. It has been shown that a combination of both controllers relating to an extension of the weighting function with a confidence range enables the definition of flexible switchover criteria as well as improved transitions between force and position control. This contributes to reduced force peaks and increased controller performance.

The force controller is integrated at the same level as the position controller so that both share the same manipulated variable. Speed and current controllers are subordinated. This structure enables switching between force and position control, as well as simultaneous usage with weighted controllers and manipulated variables. A dynamic adjustment of the weighting factors W_x and W_F is possible. The specification for the weighting function is realized in the higher-level control system. Corresponding boundary conditions and criteria are defined there, too. The experimental implementation and testing of this concept is described in the next chapters.

III. Experimental Design and Implementation

A test-setup of an electromechanical feed axis with a modern motion control from Beckhoff was selected for the implementation of the control concept and the test execution. The experimental setup is designed for loads up to 10 kN. In order to simulate a process or a resulting process force, a load module with several exchangeable spring elements was selected. In this way, variable load characteristics can be initiated with high reproducibility by a movement of the axis against the load module. The basic test-setup is illustrated in Fig. 2. A more detailed description of mechanical construction, control engineering structure as well as the comissioning and parameterization is given in [10]. In preparation for the experiments, the test setup was expanded by a top-hat rail Industrial PC (IPC), which is integrated directly via the backplane bus. This IPC replaces the external PC with the control and setpoint generation, which was connected to the other modules and terminals via EtherCAT-connection. In this way, the communication times due to the EtherCAT connection are reduced from the millisecond range to the microsecond range and the performance can be increased. The hardware and system configuration as well as the control structure were completely ported to the IPC. This includes the implementation of the control concept, the sequence programs and operating modes as well as the definition and determination of the confidence range.

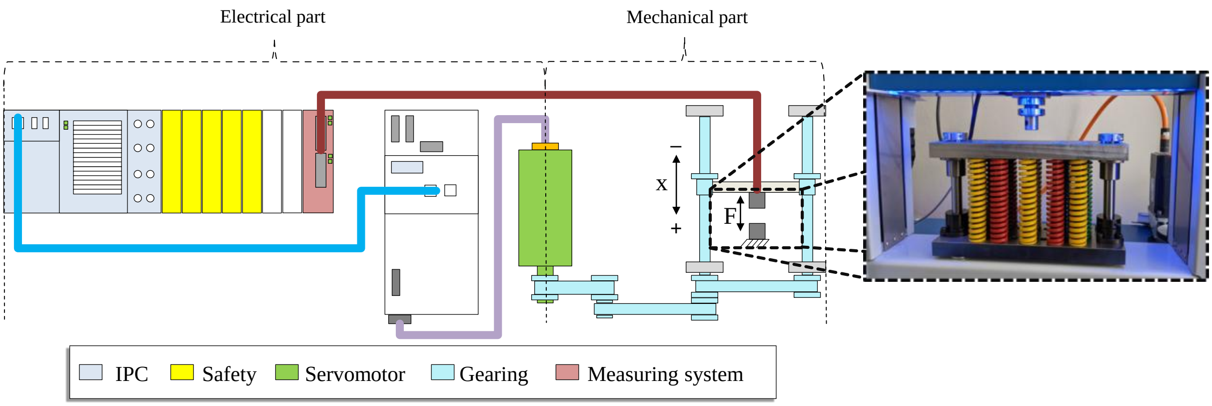

Figure 2. Experimental setup and schematic structure of the electromechanical feed axis.

The determination and definition of the confidence interval is based on the concept presented in [11]. It offers the possibility to include system knowledge and process knowledge and to use them as boundary conditions. On this basis, a lower position limit x_{force} is defined, at which the process intervention has always taken place. Only force control is active at this position. Then an upper limit x_{switch} is set, at which the hybrid transition from position control to force control begins. This value includes a safety range so that material or manufacturing tolerances can be taken into account. The position range from x_{switch} to x_{force} forms the confidence interval as illustrated in Fig. 3. In this area, the beginning of the process can take place at an unknown position, when both controllers are active. The confidence interval is used for the hybrid control with simultaneous controllers to realize the transition from position control to force control. That means only position control is active at x_{switch} and only force control at x_{force}. The hybrid transition is realized with the weighting factors W_F for force control and W_x for position control. Both are changed depending on the position. The factors are recalculated in each cycle with a cycle time of 1 ms. That is based on the actual values and the factors are adjusted accordingly in the control structure. W_x results from:

$$W_x = 1 - (x_{av} - x_{switch}) / (x_{force} - x_{switch}) \tag{1}$$

and W_F from:

$$W_F = (x_{av} - x_{switch}) / (x_{force} - x_{switch}) \tag{2}$$

Furthermore, the range limits and framework conditions for the weighting function are defined in the control's sequence program. According to the machine coordinate system, the calculation is performed only under the following condition:

$$x_{switch} \leq x_{av} \leq x_{force} \tag{3}$$

Moreover, the confidence interval is standardized so that the factors can only take on values between 0 and 1. In addition, W_F and W_x behave in a complementary manner to each other. In this way a percentage weighting is generated. The factors are transferred to the control system in every cycle via the sequence program. There they are offset against the manipulated variables of both controllers. This guarantees real-time capability. The subsequent fusion and calculation of the manipulated variables takes place via the corresponding motion control commands. As a result, both controllers are engaged at the same time in the confidence interval and influence each other during contact. This avoids a direct switch from position control to force control. At the beginning of the interval, the position controller is dominant so that contact is reliably established. As the distance becomes smaller, there is a change and the prioritization of the force controller increases. In this way, a better approximation of the nominal force curve is achieved. At the end of the confidence range, the transition is complete and only the force control is active.

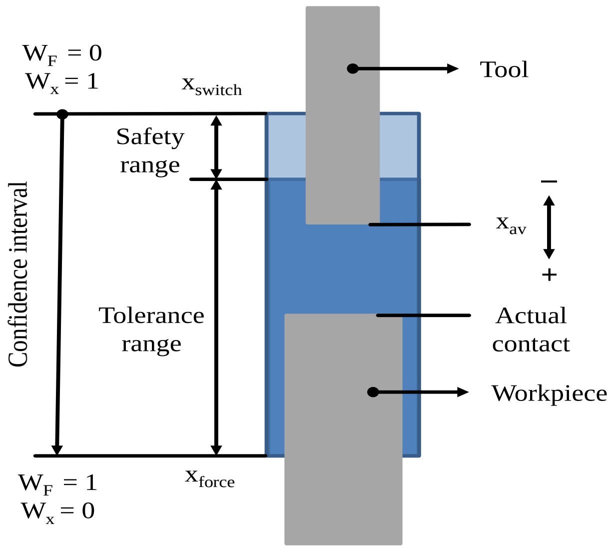

Figure 3. Definition of the confidence interval

IV. Experiments and Results

The process itself is part of the controlled system and must be included in the design procedure of the force controller. Hence, a system identification of the control plant is the first step, in order to determine appropriate parameters. The identification and excitation of the controlled system takes place by means of a step function as illustrated in Fig. 4. Setpoint value is the velocity, which represents the manipulated variable of the force controller. For practical execution, the position controller was deactivated. During identification, a stepwise excitation of 5 mm/s is activated at the input of the velocity control loop. An offset of 1 mm/s was selected in order to avoid static friction effects. The force is recorded as the output of the control plant. The result of the identification and the relevant parameters are summarized in Table I.

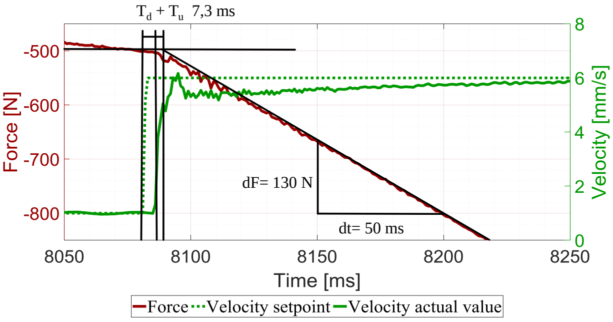

Figure 4. Identification of the controlled system

The controlled system has an integrating behavior with delay. The gain factor K_{SI} can be calculated according to the following equation:

$$K_{SI} = dF / (dt * v_{av}) \tag{4}$$

Based on the determined values, K_{SI} is 460 N/mm. The gain factor K_P for the force controller is calculated on the basis of these characteristic values. According to the results in [10], a good controller performance can be achieved with the following setting instruction:

$$K_P = 1 / (a * K_{SI} * (T_d + T_u)) \tag{5}$$

Here, the parameter a represents the damping factor, which has been set equal to 2. That results in K_P = $149*10^{-3}$ mm/Ns.

TABLE I. CONTROLLED SYSTEM PARAMETERS

Parameter	Symbol	Value
Time difference	dt	50 ms
Force difference	dF	130 N
Actual velocity	v_{av}	5.65 mm/s
Dead time	T_d	4.5 ms
Delaying time	T_u	2.8 ms

Subsequently, the influence of different impact velocities in connection with the hybrid transition and the confidence interval was examined with the optimized controller setting. For this purpose, the confidence interval was defined in a range of 1 mm. The tests were designed in such a way that the process begins at a distance of 0.5 mm from x_{force}. For the experimental proof, the exact determination of the position was carried out by approaching the contact point with a force threshold of 10 N in order to ensure the distance to x_{switch} and x_{force}. Thus, the increase in force takes place in the middle of the confidence interval. The corresponding results of the tests are shown in Fig. 5. Here, the speed and time dependencies of the confidence interval become clear. It can be seen that with higher approach speeds of the position controller, the end of the confidence interval at which the transition to force control is completed is also reached more quickly. In addition, at slower speeds, it will take longer to reach the contact point. Furthermore, the effect can be observed that smaller force peaks arise in the contact area at lower speeds. Compared to the setpoint curve F_{sp}, the force overshoots slightly at an approach velocity of 15 mm/s. However, by reducing the speed, it is possible to approach the setpoint curve without overshooting.

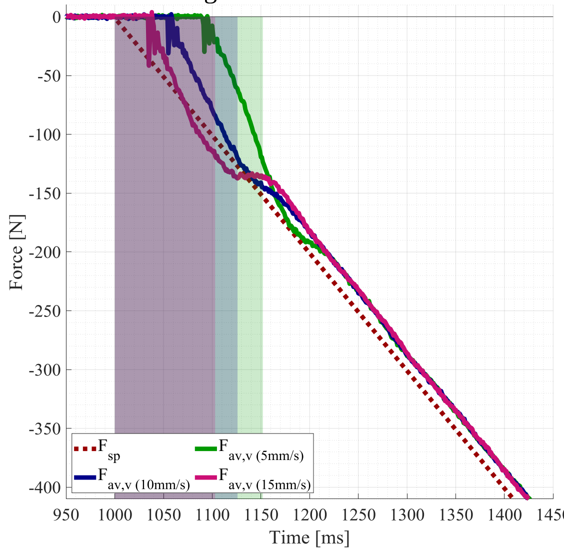

Figure 5. Velocity dependency of the confidence intervall

Furthermore, an investigation was carried out with respect to various gain factors for the force controller. The contact point remained at a distance of 0.5 mm from x_{force} in the middle of the unchanged confidence interval. The setpoint velocity from the position ramp was determined to 15 mm/s for all tests. The results are shown in Fig. 6. It can be seen that the gain factor of the force control also has an influence on the temporal duration of the confidence interval. As the gain factor increases, the position x_{force} is reached more quickly. In addition, it becomes clear that with low gain factors an overshoot of the setpoint curve can be completely avoided.

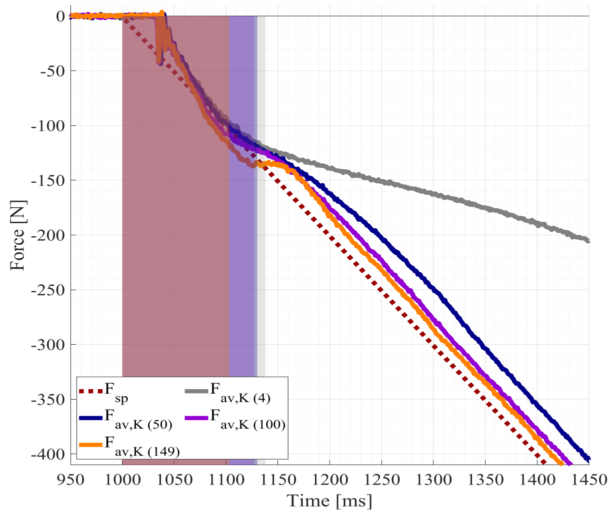

Figure 6. Influence of the force controller

However, this goes hand in hand with rapidly increasing deviations and the influence on overshoot is only slight. The gain factor K = 149*10^{-3} mm/Ns is designed towards optimal performance, so that there is little overshoot and a very good approximation of the setpoint curve. In contrast, the gain of K = 4*10^{-3} mm/Ns corresponds to the manufacturer's empirically determined setting for very high robustness. A large error occurs here and the setpoint is not reached. Therefore, the parameterization selected in this publication represents a good compromise. If overshoot shall be avoided, the gain factor can also be reduced further.

Finally, the effects of different contact points for the start of the process in the confidence interval were considered. For this purpose, contact positions were defined at the beginning, in the middle and at the end of the confidence interval. At the beginning the distance to x_{force} is 0.8 mm, in the middle again 0.5 mm and at the end 0.2 mm. An exact determination of the positions took place in advance to the experiments. The investigations were carried out with the optimized force controller setting and a setpoint velocity from the position ramp of 15 mm/s. The results are compared to the direct switchover and illustrated in Fig. 7. It can be clearly seen that the duration of the confidence interval depends very much on the actual contact. The sooner the contact occurs, the longer it takes to leave the confidence interval. It can also be seen that the delay in the contact results in a reduction in the force peaks and that these are smaller than with direct switchover. The case with an early contact (x_{con} = 0.8) represents an unfavorably designed confidence interval and shows the corresponding behavior. An overshoot occurs here that is significantly greater than with the direct switchover. In contrast, a very good approximation of the setpoint curve can be observed for the area in the middle and at the end of the confidence interval, especially in comparison to the direct switchover. These effects can be influenced by adjusting and optimizing the confidence interval. This is shown in Fig. 8. Here, the confidence interval has been increased to 1.4 mm and 1.6 mm. The contact takes place again at x_{con} = 0.8 and the other parameters have also been retained. This means that the transition starts earlier and the force controller has a higher priority. In this way, the overshoot can be significantly reduced and the approximation to the setpoint curve can be improved. Moreover, smaller force peaks can be observed in the contact area. It can also be seen that, despite the increase in the confidence interval, the duration is almost equal and only changes marginally.

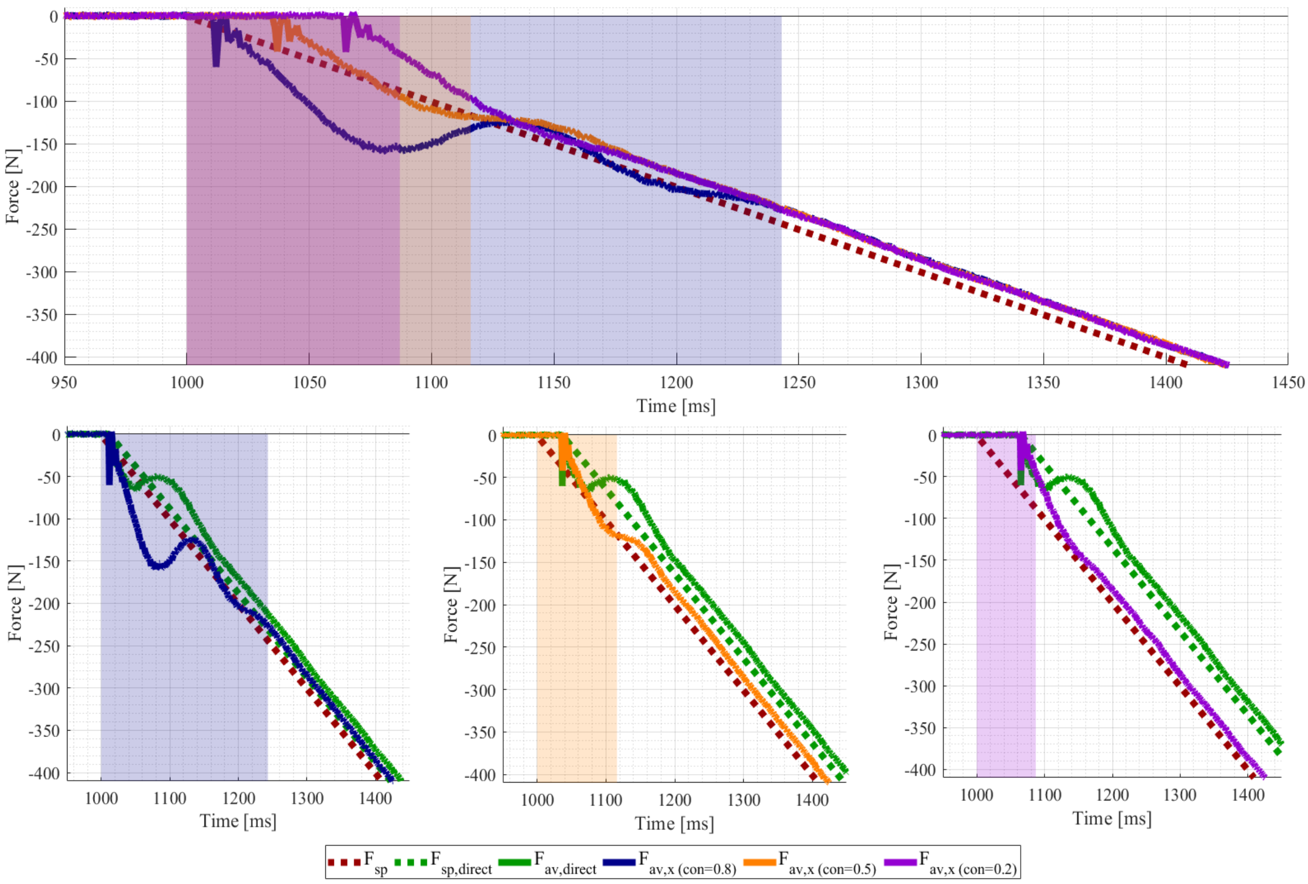

Figure 7. Control performance of switchover and hybrid transition with confidence range for different contact positions

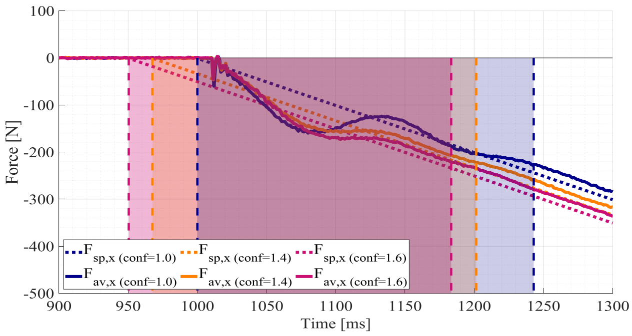

Figure 8. Influence of the confidence range

V. Summary and Conclusion

In this paper, the implementation and practical testing of a hybrid control concept for the combination of force control and position control on an electromechanical feed axis with a modern industrial motion control was described. The basics of the concept and corresponding preliminary studies for the practical implementation were also presented. Both controllers were integrated into the cascaded servo control at the same level. The controller prioritization and transition were realized in the motion control with a weighting function, which is supplemented by a confidence interval. The parameterization of the control and the definition of the confidence interval were explained in detail. In addition, various influencing factors were examined and their effects evaluated.

The experimental results have shown that the hybrid control concept enables improved transitions between force and position control as well as the definition of flexible switchover criteria. For the simultaneous use of both controllers, the definition of a suitable confidence range for the weighting function forms the basis. Compared to direct switching, the following advantages have been demonstrated:

- Smaller force peaks,
- Reduced overshoot (it is even possible to completely avoid the overshoot),
- Better approximation to the setpoint curve and
- Improved setpoint specification through the integration of the confidence range, which is delayed in the case of the direct switchover.

Furthermore, a quantitative comparison of the experimental results with the simulative investigations in [11] shows identical effects. This confirms the findings from the simulative investigations. In addition, the effectiveness of the concept for an electromechanical feed axis has been proven in practice.

However, overshoot and controller performance depend on the design and parameterization of the confidence interval and the weighting function. In this context, modeling and simulation are important support tools. It is possible to design and optimize the weighting function and the transition area in the simulation with suitable models. Besides, the development of an adaptive controller for the automatic adjustment of the controller parameters is focus in future research work.

Conflict of Interest

The authors declare no potential conflict of interest relevant to this article.

Author Contributions

André Sewohl conducted the research, analyzed the data and wrote the paper. Manuel Norberger carried out the experiments and analyzed the data. Chris Schöberlein and Armin Schleinitz edited the paper and visualization. Holger Schlegel and Martin Dix supervised the research and edited the paper. All authors had approved the final version.

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