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Advanced Control Designs for Output Tracking of Hydrostatic Transmissions

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Structured Summary of the PhD Thesis

Motivation

Hydrostatic transmission (HST) systems basically consist of a hydraulic pump, a hydraulic motor and other possible components such as pressure valves, charge pump, fluid tank and hydraulic accumulator. The presence of these components in an HST system depends on the specific configuration of the application. The working principle of the system is based on the transformation between mechanical power and hydraulic power. The hydraulic pump is coupled to the prime mover, which can be an internal combustion engine, an electrical motor or a wind turbine. Mechanical power from the prime mover is supplied to the hydraulic pump, where a pressurized fluid flow is created and transmitted along the connection hose to the input port of the hydraulic motor. Here, the hydraulic power is converted back into mechanical power at the rotational output shaft, which is coupled to the load.

HSTs – in comparison to conventional mechanical transmission systems – expose many advantages. They provide a continuously variable transmission ratio, high power density, low inertia, efficient operation in the wide range of torque-to-speed ratio, and they can serve as a dynamic braking system. The structural arrangement of an HST system is very flexible, the power can be transmitted from a single prime mover to several load locations, even if the position and orientation of the load units change. They are widely used in heavy working machines and off-road vehicles such as harvesters, wheel loaders, excavators, telehandlers, construction and agriculture machinery. In recent years, in the framework of emission reduction and environment-friendly applications, HSTs are employed in new designs of high performance working vehicles, in modern automobiles and in green energy power plants.

The limitation of HSTs in high-performance applications is caused by the energy efficiency and control issues. From a control point of view, they are characterized by high nonlinearity, disturbances and unavoidable parameter uncertainty caused by many physically related aspects such as kinematic viscosity, fluid temperature variations, leakage fluid flow and the elasticity of the hydraulic hoses. Currently, the PID (proportional-integral-derivative) controller is still predominant in HST applications but its performance, however, is not adequate to maintain an accurate tracking in the wide range of the HST operation. Therefore, advanced control approaches are obviously beneficial. In the last decade, many nonlinear control approaches have been proposed, with a huge diversity in terms of the control strategy, control objective and design principle. Nevertheless, some directions are still worth of a deeper consideration. From a practical point of view, for example, the design model should be simple to reduce the modeling effort as well as the number of parameters to be identified experimentally. Nevertheless, the resulting tracking performance of the closed-loop system should be high according to certain quality criteria, which has to be guaranteed by dedicated components of the control structure and appropriate design techniques. Moreover, due to aging or degradation, models established for a new device are prone to become less accurate during its lifetime. It may be expected that this drawback is more critical for a highly sophisticated design model. The idea is, hence, to base the control design instead on a simple design model that captures only the most decisive characteristics of the real system like the relative degree and to estimate the resulting modeling errors online as well as to use them for compensation purposes. Based on the existing control techniques which have been proposed generally for uncertain nonlinear systems, the work in this dissertation focuses on the design and validation of advanced control approaches for output tracking of HST systems.

Main Contributions

Control allocation: In practical applications with HSTs, the highest torque possible at the motor shaft is usually required, especially at low speed when starting. The high torque allows for larger accelerations of the vehicles or is beneficial during the loading phase of working machines. Moreover, the hydraulic motor also offers a higher volumetric efficiency at large displacement. Therefore, it is preferred to maintain the motor displacement as large as possible. Taking these practical considerations as the guideline, a new trajectory planning scheme for the control of HST systems is developed: both the hydraulic pump and motor are controlled simultaneously to provide the required output and, in addition, the proposed control designs are capable of fully exploiting the wide operation range of the HSTs within the system configuration limits. Accordingly, the control allocation is implemented as follows: The primary control – hydraulic pump control – is prioritized which provides efficiency. The pump displacement unit is controlled to accurately track the output. The secondary control – hydraulic motor control – is activated only when it is required to gain the proper transmission ratio. The activation mechanism is empirically scheduled depending on the desired value of the motor angular velocity. This control allocation scheme offers a higher performance and efficiency in practical applications.

Advanced Control Designs: Based on the proposed control allocation scheme, simple design models or even purely data-driven models are deployed to develop and investigate several control strategies for HSTs. These control strategies efficiently use both the pump and motor (both primary and secondary controls) synchronically to accurately track the required output – which corresponds to a multiple-input single-output control scheme – while the volumetric displacement of the hydraulic motor is still kept as large as possible. In terms of the control structures, most of the control approaches are subject to decentralized structures (except the model predictive control), where the control of hydraulic pump and motor are designed separately but in compliance with the proposed control allocation. The advanced control designs may be classified into four principle groups, where in each group several variants of the control methods are investigated.

Optimization-based approaches: This group consists of model-based control designs deploying the full system model, which comprises nonlinear model predictive control, fuzzy-based optimal control and state-dependent integral state feedback control. These approaches derive the control laws based on the solution of optimization problems or the solution of algebraic Riccati equations in the case of linear quadratic problems. Using model predictive control, state and input constraints can be addressed properly and included in the control design. Moreover, gain-scheduled tracking controllers can be derived using Takagi-Sugeno fuzzy techniques in combination with optimal control or state-dependent Riccati equation (SDRE) techniques based on system descriptions with state-dependent matrices and vectors.

Estimator-based feedback linearization: This group includes feedback linearization using a reduced-order disturbance observer, feedback linearization by means of online adaptive parameter estimation and feedback linearization using a multiple-layer perceptron (MLP) neural network. These approaches consider the nonlinear input-output relationship, and different estimators are used for the compensation of nonlinearities and disturbances resulting in an integrator chain. Subsequently, linear methods can be applied to stabilize the tracking error. In these designs, known model parts are included in the right-hand side of the state-space representation of the design model, whereas unknown model parts – typically sophisticated nonlinear descriptions for nonlinearities or uncertainties – are considered by different types of estimators. Thereby, both the robustness and accuracy are improved.

Active disturbance rejection: This group consists of two variants – an approach using an extended state observer and flat-filtering-based designs. The control approach originates from classical PID control, exploits its advantages and extends it to a higher complexity level towards generalized PID control. For its application, only knowledge or assumptions on the relative degree of an input-output relation are necessary, namely, the complete right-hand side of the state-space representation of the design model is considered as unknown. Different techniques are applied to provide either observer-based estimates for the unknown model part or to design a compensator using flat-filtering techniques.

Model-free control approaches: There are three robust control structures investigated - sliding mode control, feedback error learning and adaptive feedforward compensation. The control approaches in this group do not require any model knowledge and may result in data-driven control structures whose control law are based on either output measurements or tracking errors as well as its time derivatives. The robustness and performance of such control structures are promising.

The use of tracking differentiators – which can be interpreted as a model-free way to determine time derivatives of noise-afflicted measurements and substitute classical state transformations corresponding to a classical model-based approach – is investigated in many of mentioned control structures above – if applicable, which provides a practical way for an effective and robust control design for HST systems.

Test scenarios: Each of the control designs is studied in two application scenarios: In the first scenario, the hydraulic pump speed and the load torque are held constant. For the second test scenario, both the hydraulic pump angular velocity and external load torque acting on the motor output shaft are assumed to vary periodically. This mimics the working conditions in real applications where the prime mover changes the angular velocity due to external effects or due to the commands of the operator. In addition, the load may also vary due to external resistances. Such conditions happen frequently in applications of HSTs in wind turbines or in working machines.

Discussion of the Results

Study results: The control designs with the proposed control strategy provide efficient methods for the control of HST systems in a wide working range, their performance has been analyzed and validated by means of both simulation using the validated mathematical model and experiments on the real equipment. Their performance under the test scenarios is assessed, quantified and compared. The results show an equivalent control performance for all control structures, which include both model-based and model-free design approaches. However, there are distinctions between them regarding the control performance in different test cases on the real system. The corresponding performance is evaluated by a common criterion – the root-mean-square (RMS) error – for both velocity and hydraulic torque controls. The proposed control designs can be divided into two groups regarding their robustness: The first group consist of model-based approaches such as feedback linearization using reduced-order observer, nonlinear model predictive control, fuzzy-based optimal control and state-dependent integral state feedback control. The RMS error evaluation shows very accurate control results in the first test case, where the prime mover speed and disturbance load torque are constant. However, in the second test case – where the prime mover speed and external load torque vary intensively – the model-based designs exhibit their limits. Though the tracking accuracy is still maintained, the performance degrades significantly with the increasing RMS error of 71.4% up to 85.7%. The second group comprises active disturbance rejection approaches, feedback linearization using a neural network, feedback linearization using adaptive parameter estimation and the model free approaches. In the first test case, these approaches provide an equivalent control accuracy in comparison to one of the first group controls. In the second test case under the impacts of disturbances, however, they present a superior behavior with more robustness and a smaller increase in the RMS error of 18.7% up to 33.6% only. Though the disturbances are not completely rejected, the tracking accuracy is much improved. These results certainly are closely related to the design method of these controls, where the requirement for a complete model is reduced or even not necessary.

Future improvements: From an overall perspective, all of the proposed control designs show their applicability for an accurate control result of HST systems. With two test cases investigated in this application research, the characteristics of each designed control are somehow revealed. However, this research conducts the tests in a short time horizon, the changes of the physically-related aspects such as temperature, viscosity, elasticity are small and may not be enough to have a significant impact on the controllers. Therefore, for a practical application objective in the future, the controls need to be tested with more realistic working conditions and, moreover, with longer running time that increases the level of uncertainty in the system.

Further improvement of the tracking performance may be achievable on HST systems with learning methods which provide high robustness, accuracy and simplicity in control designs. In this study, the hydraulic motor is controlled separately to gain the proper transmission ratios while keeping the hydraulic torque as high as possible. The resulting hydraulic torque, however, is not optimized. Therefore, a learning control structure – that adjusts both control inputs to hydraulic pump and motor simultaneously – should be investigated.