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A Decomposed Co-design Strategy for Continuously Variable Transmission Design

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Abstract—This paper presents a decomposed co-design optimization framework to jointly design the geometry and the controller of a Continuously Variable Transmission (CVT), accounting for its low-level dynamics. Specifically, we first devise a model of the CVT and the feedback controller, and use it to formulate the optimal co-design problem with the goal of minimizing the transmission’s mass as well as the losses that occur in the system, including the lower-level actuation. Second, we divide the resulting nonlinear multi-objective optimization problem into separate hierarchical optimization subproblems and we leverage the concept of Analytical Target Cascading (ATC) to solve the separate optimization subproblems using an interior-point optimization algorithm. Finally, we showcase our framework on a representative drive cycle. Our results demonstrate that the presented co-design method can achieve a more compact CVT design without compromising the desired ratio trajectory, and even reducing the overall losses by 23%.

Index Terms—optimization, multi-objective optimization, continuously variable transmission, co-design, system design, simultaneous design

I. INTRODUCTION

Demands on reducing the cost of ownership of vehicles as well as their energy consumption have increased significantly over the past decade. In order to meet this design requirement, optimal vehicle design strategies have been well researched in the literature, including the development of suitable energy management control strategies [1], [2], and in combination with optimal powertrain component sizing [3].

One way to achieve an efficient vehicle energy consumption is by utilizing a Continuously Variable Transmission (CVT), which allows the primary power source to be operated at the operating points that correspond to the highest energy efficiency regions [4], [5], which then results in an improved vehicle driveline energy consumption. The general CVT shown in Fig. 1 is comprised of several subsystems, namely a variator that consists of a set of conical pulley sheaves and a belt to transmit power from the propulsion source; an actuation system, which is connected to the variator system and actsuates the pulley sheaves during CVT operation; and the control subsystems, ensuring that the transmission meets the required performance. While a CVT in theory can realize an improved powertrain energy consumption, this transmission still has a significant drawback: Compared to other types of vehicle transmission, a belt-driven CVT has a relatively lower efficiency (84%), whereas a manual (MT) and automatic transmissions (AT) typically have a system efficiency of around 96% and 85%, respectively [6]. One of the main contributors of the CVT’s energy consumption is the actuation system. Against this backdrop, our paper proposes an optimization framework to co-design CVTs accounting for their actuation system.

A. Literature Review

Several integrated plant and control system design methods have been proposed in literature [7], [8]. For large-scale systems that consist of multiple components, the implementation of a simultaneous co-design method may not always be feasible due to memory limitations. A possible solution to overcome this challenge is by partitioning the problem into multiple subproblems, which is not uncommon in traditional system design. However, due to the dependency between the corresponding subsystems, solving the smaller design tasks must be properly coordinated in order to achieve the optimal design [9]. In the field of system design optimization with multiple subsystems, researchers have studied different decomposition methods for optimal system design, including Multidisciplinary Design Optimization [10], [11] and Analytical Target Cascading (ATC) [12], [13]. In particular, ATC has been shown to be an effective coordination method of decomposed optimization strategies [14], [15].

In the context of powertrain optimization, researchers have leveraged derivative-free optimization methods [16], [17], as well as convex optimization algorithms [18], [19]. Yet, these methods do not explicitly consider the design of the transmission (i.e., its physical properties and the controller). In order to improve the CVT energy efficiency and performance,
several approaches have been proposed in the literature, including physically redesigning the CVT [20] and formulating an advanced control strategy for the system [21]. However, there is no framework that can concurrently design the CVT’s geometry and control, whilst accounting for its low-level actuation system, where arguably a significant part of the losses occurs.

B. Statement of Contribution

To bridge this gap, we present a decomposition-based design optimization framework for CVT systems which consists of the variator and the actuation system. In a previous study [22], a simultaneous integrated plant and control design of a CVT at the variator level has been conducted. In this work, we extend the problem formulation by including the lower level actuation system controller design. The proposed design problem is solved using a decomposed co-design approach spanning multiple subsystems (variator and actuation) based on the ATC design framework.

II. MODELING

This section elaborates the modeling and the description of the design subject. By horizontally moving the pulley sheaves on both the primary and secondary sides, the ratio of the input and output speed of a CVT is varied, which is done by the actuation system. A more detailed modeling of a CVT and its working principles can be found in [22], [23]. From now on, for the sake of simplicity, we drop the notation of time dependence whenever it is clear from the context.

Below, we focus on the description of the electro-hydraulic actuation system depicted in Fig. 2. This type of actuation system consists of two servomotor-actuated pumps, namely a shifting pump and a clamping pump. In order to horizontally move the pulley sheaves and provide the required transmission ratio during operation, the shifting pump generates a pressure \( p_{sh} \) that must match the primary clamping pressures \( p_p \). Consequently, the clamping pump, which is connected to the oil reservoir, supplies a pressure \( p_{cl} \) that must match the secondary clamping pressure \( p_s \) to prevent the belt from slipping. Hence, in this case, the pressures generated by the pumps should be able to match the clamping pressures required at the variator level (i.e., \( p_p = p_{sh} \) and \( p_s = p_{cl} \), as shown in Fig. 2). This indicates the coupling between the variator and the actuation subsystems.

A. Actuation System Dynamics

The dynamics of the electro-hydraulic actuation system is expressed as

\[
P_{sh} = \frac{E_{sh}}{V_{sh}}(V_{e,sh}\omega_{sh} - A_p v_p - Q_{1,sh})
\]

\[
P_{cl} = \frac{E_{cl}}{V_{cl}}(-V_{e,cl}\omega_{cl} - V_{e,sh}\omega_{sh} - A_s v_s - Q_{1,cl})
\]

\[
\omega_{sh} = \frac{1}{J_{sh}}(T_{sh} + V_{e,sh}(p_p - p_s) - b\omega_{sh} - T_{cl,sh})
\]

\[
\omega_{cl} = \frac{1}{J_{cl}}(T_{cl} + V_{e,cl}(p_s - p_{atm}) - b\omega_{cl} - T_{1,cl})
\]

where \( p_{sh} \) and \( p_{cl} \) denote the pressure generated by the shifting and clamping pumps, respectively. \( \omega_{sh} \) and \( \omega_{cl} \) are the shifting and clamping pump rotational speed which is supplied by the servomotors. \( v_p \) and \( v_s \) are the primary and secondary pulley displacement speed. \( E_i \) is the bulk modulus of the oil, \( V_{e,i} \) is the pump displacement volume, \( J_i \) is the servomotor inertia, \( \omega_i \) is the servomotor rotational speed, \( T_i \) is the motor torque, and \( b \) is the motor friction coefficient for \( i \in \{sh, cl\} \).

B. Actuation Losses

Here, the losses at the actuation level are those generated by the gear pumps. Such losses are due to flow and hydro-mechanical losses of the pumps, and are given by

\[
P_{l,pump} = P_{l,flow} + P_{l,hm}
\]

where the flow loss is modeled as

\[
P_{l,flow} = \sum_{i \in \{sh,cl\}} Q_{1,i} \Delta p_i
\]
whereby \( p_l \) is the pump-generated pressures, and \( Q_{l,i} \) is the pump flow losses for \( i \in \{sh, cl\} \), referring to the shifting and clamping pumps, respectively. Furthermore, the hydromechanical losses are given by

\[
P_{l,hm} = \sum_{i \in \{sh, cl\}} T_{l,i} \omega_i,
\]
where \( T_{l,i} \) depend on the pump torque losses and the rotational speed. The flow losses \( Q_{l,i} \) (in \( \text{L/min} \) or \( m^3/s \)) of the pumps are expressed as functions of the pressures, such that

\[
Q_{l,i} = C_s \frac{V_e \Delta p_i}{2 \mu \omega_i} + C_p p_{in,i},
\]
where \( V_e \) is the pump displacement volume (\( m^3/\text{rad} \)), \( \mu \) is the fluid viscosity constant. The corresponding pump pressure difference \( \Delta p_i \) is expressed as

\[
\Delta p_i = \begin{cases} p_p - p_{sl} & \text{for } i = \text{sh} \\ p_p - p_{atm} & \text{for } i = \text{cl}. \end{cases}
\]

Additionally, the input pressures corresponding to the pumps are given by

\[
p_{in,i} = \begin{cases} \min\{p_p, p_s\} & \text{for } i = \text{sh} \\ \min\{p_s, p_{atm}\} & \text{for } i = \text{cl}. \end{cases}
\]

Furthermore, the torque losses \( T_{l,i} \) that contribute to the hydromechanical losses are expressed as a function of the pressures as well as the servomotor rotational speed, such that

\[
T_{l,i} = C_l \frac{V_e \Delta p_i}{2 \mu \omega_i} + C_{dl} \omega_i^2 + C_{in,p} p_{in,i},
\]
where the coefficients \( C_s, C_p, C_l, C_{dl}, \) and \( C_{in,p} \) are fitted parameters obtained from measurement.

### III. METHODOLOGY

We present a decomposed co-design strategy for CVT variator and actuation system design based on an ATC framework. We divide the integrated system design problem into two separate hierarchical optimization subproblems. The top-level subproblem passes down the target variables (in our case, the required clamping pressures \( p_{cl} \) and \( p_{sh} \)), as well as the additional plant design parameters that influence the actuation system dynamics to the low level subproblem. The lower level optimization subproblem tries to match the target variables by generating its response variables (in our case, these are denoted by \( p_{sh} \) and \( p_{cl} \)). A more detailed formulation of a general ATC framework can be found in [12].

#### A. CVT Co-design Objective

The objective of the CVT co-design problem is to minimize the transmission mass as well as the losses that occur in the system (i.e., the leakage and the actuation system losses). The plant design parameters are the variator parameters \( x_p = [\beta, R_1, R_2] \) and the control design parameters \( x_c \) include the variator controller gains \( K_p \) and \( K_i \), as well as the optimized servomotor torques \( T_{sh} \) and \( T_{cl} \), such that \( x_c = \{K_p, K_i, T_{sh}, T_{cl}\} \). More details on the derivation of the corresponding models of the variator design problem are discussed in [22]. In this work, the complete CVT system design problem is stated as

\[
\min_{x_p, x_c} w_{p} M_{e}(x_p) + \int_{0}^{t} \left[ w_{C1} P(x_p, x_c) + w_{C2} P_{pump}(x_p, x_c) \right] dt
\]
subject to:

\[
\beta \in [\beta, \overline{\beta}], R_1 \in [R_1, \overline{R_1}], R_2 \in [R_2, \overline{R_2}],
\]

\[
r_{cl} = 2 \omega_{cl} (\Delta T_1 + \omega_{sh} \omega_{cl}) \frac{c}{c_{cl}} (r_{cl}(t) u(t),
\]

\[
P_{l, var} = C_{p} p_{p}^2 + C_{p2} p_{p}^2,
\]

\[
p_{p}(t) = \frac{F_{p}(t)}{A_p} - \frac{F_{cl}(t)}{A_p} \frac{p_{s}}{A_s},
\]

\[
F_{cl}(t) = \frac{\cos(\beta) (|T_p(t) + S_i T_{max}|) t}{2 \pi \rho \omega_{cl}},
\]

\[
F_{p}(t) = \exp\left[ u(t) + \ln \frac{F_{p1}}{F_{p2}} \right] F_{p0}(t),
\]

\[
\omega(t) = \frac{u_{na}(t)}{2 \omega_{p}(t) + \frac{1 - \cos(\beta)}{2\sin(\beta)} c_{cl}(r_{cl}(t))}
\]

\[
u_{na}(t) = -K_{p} e(t) - K_{i} \int_{0}^{t} e(\tau) d\tau,
\]

\[
P_{l, pump} = \sum_{i \in \{sh, cl\}} Q_{l,i} \Delta p_i + \sum_{i \in \{sh, cl\}} T_{l,i} \omega_i,
\]

\[
\dot{p}_{sh} = \frac{V_{sh}}{V_{sh} + V_{sh} \omega_{sh} - A_p p_{p} - Q_{l,sh}}
\]

\[
\dot{p}_{cl} = \frac{V_{cl}}{V_{cl} - V_{sh} \omega_{sh} - A_s v_s - Q_{l,sh}}
\]

\[
\omega_{sh} = \frac{1}{J_{sh}} (T_{sh} + V_{sh} (p_{p} - p_{s}) - b_{w} \omega_{sh} - T_{sh})
\]

\[
\omega_{cl} = \frac{1}{J_{cl}} (T_{cl} + V_{sh} (p_{p} - p_{atm}) - b_{w} \omega_{cl} - T_{cl})
\]

where the actuation losses \( P_{pump} \) are described in (7)–(13).
The decomposed co-design optimization framework is performed in an iterative manner. First, we start by initializing the values of $p_T^0$ and $p_T^*$, and solve the lower level subproblem utilizing these initial values. Then, using the optimized values of $p_{sh}^R$ and $p_{cl}^R$, the upper level, we solve the upper level optimization problem, obtaining $p_T^p$, $p_T^*$, which will become the targets for the lower level optimization subproblem. Furthermore, we solve the lower level subproblem again (now with the new values of $p_T^p$ and $p_T^*$ generated by the upper level subproblem). This completes one iteration. The iterative process is repeated until the termination criterion is reached, that is when $\epsilon_p$ and $\epsilon_s$ are within a desired tolerable value, given by

$$\epsilon_p \leq \epsilon_{p,tol}, \quad \epsilon_s \leq \epsilon_{s,tol},$$

where $\epsilon_{p,tol}$ and $\epsilon_{s,tol}$ are the user-defined maximum tolerance values of the discrepancies between the target and response variables. Small values of $\epsilon_p$ and $\epsilon_s$ enforce the shared variables of the top and bottom level to not deviate from each other, ultimately yielding trustworthy results.

### IV. Results

This section discusses the results stemming from the proposed co-design approach. We discretize the subsystems’ dynamics with the Euler Forward method. The decomposed optimization subproblems are solved using the IPOPT solver [25] provided by the OPTI toolbox for the MATLAB interface. The optimized design results presented in this section are obtained over a selected dynamic cycle, namely, the New European Drive Cycle (NEDC). In this study, we consider an internal combustion engine vehicle. Thereby, we generate a reference CVT ratio trajectory $r_{g,ref}(t)$ operating the engine at the Optimal Operation Line (OOL), i.e.,

$$r_{g,ref}(t) = \frac{\omega_{wh}(t)}{\omega^\star_e(t) \cdot r_{fd}},$$

whereby $\omega_{wh}(t)$ is the required wheel rotational speed that is determined by the drive cycle, $r_{fd}$ is the final drive ratio, which is chosen as a constant, and $\omega^\star_e(t)$ is the optimal engine speed yielding the minimum fuel consumption. The results of the proposed design framework for different values of weighting parameter $w_P$ are summarized in Table I. Additionally, the results are compared to a baseline design of a commercial CVT available for passenger cars.

Fig. 4 depicts the Pareto front stemming from the proposed optimization problem for various optimization weights. When more emphasis is placed on minimizing the losses, the transmission mass gets larger. In contrast, the more emphasis is placed on minimizing the mass, the larger the resulting system losses become, indicating a trade-off between the plant and control objectives. Crucially, our framework can significantly outperform the baseline solution with regard to both the losses and the mass (cf. the solution marked in green in Fig. 4).

We can discern from Fig. 5 that the optimized CVT design is capable of accurately realizing the desired ratio trajectory yielding minimum energy consumption. Furthermore, it is also visible that the shared variables between the decomposed
optimization subproblems converge to the same values, as shown in Fig. 6. However, the optimization problem present in this paper is of a nonlinear nature, hence different initial values can influence the obtained optimization results. The selection of the tolerance error can also affect the performance of the optimization framework. However, this can vary for different values of optimization weights, as shown in Table I. The proposed framework with \( w_P = 0.999 \) and \( w_C = 1 \) takes 2 iteration steps before converging to the acceptable tolerance error between the response and target variables, as depicted in Fig. 7. It is shown that the optimized CVT is 5% lighter in terms of variator mass, and the occurring losses can be reduced by 23%.

Furthermore, we investigated the impact of the weighting parameters on the obtained design results. The obtained results showed that different weighting parameters can have an influence on the optimized system design parameters. Moreover, it was found that the total computation time of the proposed optimal design framework depends on the number of iterations that the subproblems take to converge, and relies on the initial values supplied at the start of the algorithm, the complexity and the scale of the design problem, as well as the coupling strength between the subproblems. Besides, the selection of the weighting parameters for the allowable deviations at the upper level optimization subproblem \( (w_{\epsilon_P} \text{ and } w_{\epsilon_S}) \) can also have an impact on the convergence of the proposed design framework.

V. CONCLUSIONS

In this paper, we have presented the results of a decomposed co-design approach for a Continuously Variable Transmission (CVT) including the actuation system. We demonstrated that our proposed approach is capable of solving the multi-level (variator and actuation system) CVT co-design problem pre-
sented in this work within a reasonable amount of computation time. The Analytical Target Cascading (ATC)-based co-design approach presented in this work dissected the optimal CVT variator and actuation system design problem into two separate subproblems by exploiting the hierarchy that exists in the system. Furthermore, we showed that the obtained design results as well as the time it takes the algorithm to converge are influenced by the selection of the weighting parameters.

Although the decomposed strategy may result in a larger total computational time (due to the iterative process), the smaller subproblems are computationally easier to solve compared to the simultaneous approach, which can sometimes result in too-large problems. Hence we can exploit the ATC-based approach as an alternative formulation of a co-design of large-scale systems where the standard simultaneous plant and control optimization framework cannot be implemented.

In the future, we are interested in comparing the results of the proposed design framework with that of traditional system design, namely sequential methods and/or iterative strategies. Furthermore, possible extensions of this research line could incorporate the design optimization of a complete vehicle powertrain system, finding the optimal sizing of the components and the energy management, and designing the optimal CVT (the physical parameters and the corresponding controllers over the multiple subsystems) suitable for the vehicle under consideration.

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