Integrated Controller-Topology Optimization for Motion Systems

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Abstract

Topology optimization has been a popular tool for structural design and is successful at increasing performance, such as maximum stiffness or eigenfrequencies [1]. However, topology optimization for structural design involving a (PID) controller to improve closed-loop performance is still challenging. In this work a new method is presented to perform integrated controller-topology optimization for SISO systems.

Van der Veen *et al.* [2] provide a first optimization method for integrated controller-topology optimization for a motion system for maximum bandwidth, closed-loop stability, and disturbance rejection properties. The disturbance rejection properties of the system are assured by directly constraining the maximum value of each peak in the sensitivity function. However, a numerical search algorithm needs to be used as these peaks cannot be calculated explicitly. Additionally, the number of peaks (and thus the number of constraints) can change during the optimization, possibly leading to discontinuous behavior and oscillations, which is unfavorable for the iterative gradient-based optimization process. Also separate constraints are required to ensure the closed-loop stability (using the closed-loop poles), as limiting the sensitivity function is not a sufficient condition for stability. Combined, these characteristics of the method hamper optimization convergence and impede application to industrially relevant problems. Therefore there is need for improved methods for integrated controller-topology optimization.

In this contribution, we present an alternative approach based on formulating the optimization problem using the Nyquist curve. Using a geometric approach on the Nyquist curve is better suited for optimization of SISO systems, as stability and disturbance rejection properties (modulus margin) can be imposed by preventing encirclements of the -1 point and ensuring a minimum distance to the -1 point, respectively (see Fig. 1). Van Solingen *et al.* [3] use a similar geometric approach, but require many constraints sampled at different frequency points. This is computationally infeasible for topology optimization, as a finite element solution is required for each constraint per design iteration.

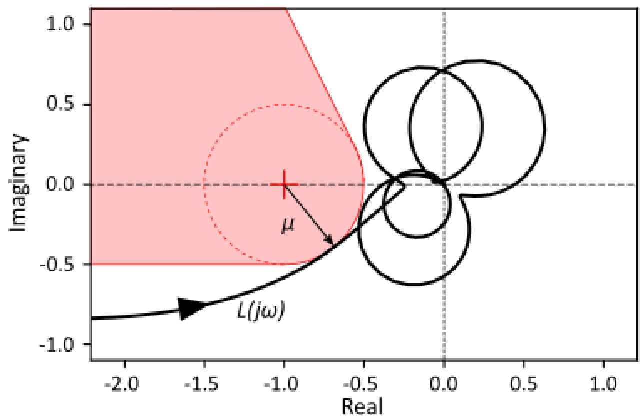

Figure 1: Illustration of geometric stability and disturbance rejection criteria. The Nyquist curve is not allowed to enter the area shared in red, with modulus margin μ.

Our method enables controlling the global shape of the Nyquist curve efficiently using only a limited number constraints, using local approximations of the Nyquist curve based on circles (Fig. 2). Close to the frequency of each flexible eigenmode, the Nyquist curve behaves like a circle [4]. Therefore, by approximating the Nyquist curve locally with different circles for each eigenmode, the entire curve can be characterized using simple geometry. The overall shape of the Nyquist curve can now be influenced during optimization, by limiting the position of each circle in the complex domain. It is after all straightforward to calculate the shortest distance from the circle to, for instance, the -1 point and use this in a constraint. The number of constraints becomes equal to the number of approximated circles (and number of eigenmodes), which provides a significant reduction compared to sampling a discrete grid of frequencies.

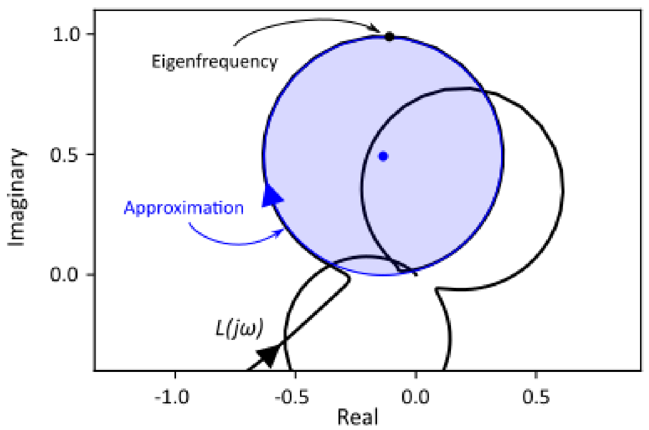

Figure 2: Local circle approximation indicated in blue of one of the flexible eigenmodes in the system.

Using the circle approximations, an integrated controller-topology optimization problem can be formulated in an efficient and differentiable manner, which allows for stable and efficient optimization. This is demonstrated using a test-case of a motion platform with one rigid-body mode (vertical translation) and including 10 flexible eigenmodes. It is controlled by a PID controller with additional low-pass filter, based on industry standard rules-of-thumb [5]. The motion platform is optimized for a maximum bandwidth, subject to requirements on modulus margin and closed-loop stability, by keeping the circles outside of the red area indicated in Fig. 1. A design optimized simultaneously for three different sensor positions to account for position dependency is shown in Fig. 3, with corresponding Nyquist plot for the three outputs. The obtained bandwidth is significantly higher (up to 350% in this example), as compared to a design obtained with topology optimization for maximum eigenfrequencies.

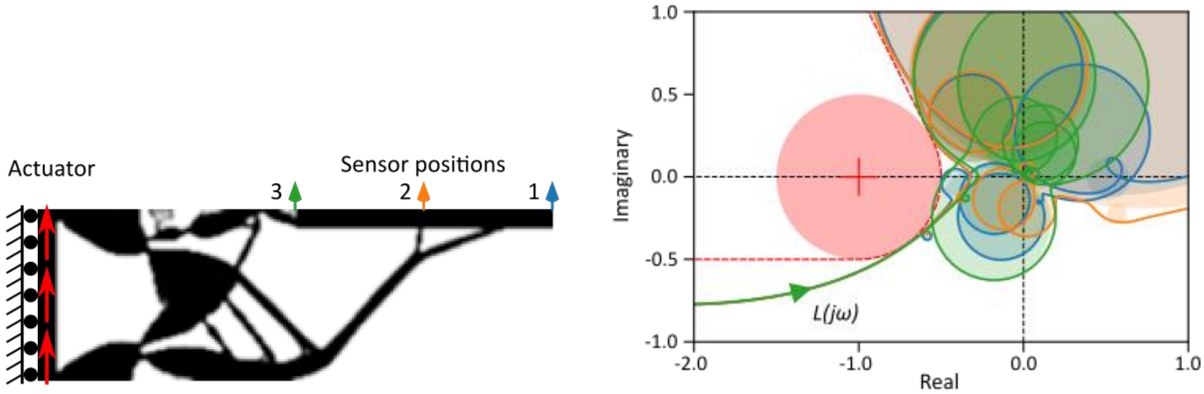

Figure 3: Optimized design and corresponding Nyquist plot for the three different sensor positions.

Extension to MIMO systems might be possible using methods such as sequential loop closing, however multiple loops are interacting with each other in a truly coupled MIMO system, affecting the closed-loop behavior. Therefore, further research is needed regarding the application to MIMO systems. Also the inclusion of effects as time delay and the use of more advanced controller structures are identified as important topics for future work.

Using this optimization formulation, SISO systems can be optimized in a simple and computationally efficient way. Using an example of a motion stage, the system performance in terms of bandwidth is improved significantly compared to designs optimized for maximum eigenfrequencies, while satisfying the required modulus margin. Also position-dependent dynamics can be accounted for by constraining local approximations of multiple Nyquist curves. All in all, the proposed formulation based on circle approximations of the Nyquist curve provides a promising new direction for integrated controller-topology optimization for next generation motion systems.

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