Chapter 2
Review of Linear and Nonlinear Controller Designs

This Chapter reviews several flight controller designs for unmanned rotorcraft.[1] Flight control systems have been proposed and tested on a wide range of rotorcraft types and configurations. This review includes controller designs for several rotorcraft types such as full-scale, small-scale and experimental platforms (gimbaled on a vertical stand). Existing flight control systems use tools from all fields of control theory by incorporating into the controller design classical, modern and intelligent control techniques.

Regardless, flight control systems are mainly classified as linear or nonlinear. Typically, this classification is based on the rotorcraft model representation that is used by the controller. Linear control designs are more application-oriented and have been implemented on the majority of rotorcraft platforms. Their popularity stems from the simplicity of the controller design, which minimizes both the computational effort and the design time.

On the contrary, nonlinear controllers are mostly valued for their theoretical contribution to the rotorcraft control problem and their implementation to actual platforms is limited. In what follows, both linear and nonlinear controller designs are discussed and compared.

In general, the attitude dynamics of the helicopters are significantly faster compared to its translational dynamics. The architecture of both controller types (linear and nonlinear) is adapted to this distinct time scaling between the two helicopter subsystems. To this extent, most helicopter controllers are composed of two interconnected feedback loops as shown in Fig. 2.1. The outer feedback loop is responsible for the regulation of the translational dynamics. It is used for guidance, generating position or velocity reference commands to the inner-loop. In addition, it controls the magnitude of the thrust vector by the collective command. The inner-loop is responsible for stabilizing the helicopter and decoupling the attitude variables by controlling the helicopter moments. The main task of the inner-loop is to provide adequate decoupling such that the outer-loop may control each variable of the translational dynamics subsystem independently.

[1] The term rotorcraft and the term helicopter are used interchangeably in this book.

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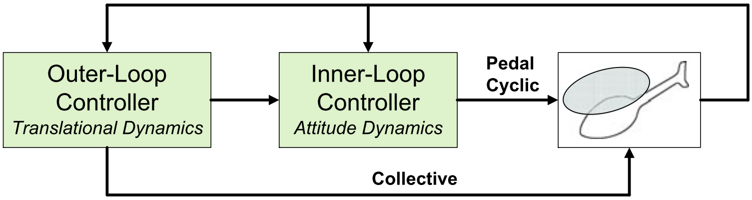

Fig. 2.1 Inner-loop and outer-loop control architecture for helicopters

2.1 Linear Controller Designs

Classical control techniques disregard the multivariable nature of the rotorcraft dynamics and the strong coupling that exists between the rotorcraft states and the control inputs. In controller designs of this type each control input is responsible for the regulation of one particular rotorcraft output. The interaxis couplings that exist between the rotorcraft outputs are disregarded, and each control input is associated with an SISO feedback loop. The SISO feedback loops that correspond to the control inputs are completely independent of each other. The SISO feedback loops are designed based on typical loop shaping techniques. The stability of a feedback loop is determined by the phase and gain margins of the latter. These margins dictate the admissible amount of gain and phase that can be injected by the controller such that the feedback loop dynamics are stable. These margins, however, may easily lead to misleading conclusions in the case of multivariable systems [108].

A PID controller that is composed of four independent SISO loops has been applied to the *Kyosho Concept 60 Graphite* small-scale radio controlled helicopter [88] as part of the *Berkeley AeRobot* (BEAR) project. In order to evaluate the closed loop characteristics of the PID scheme an eleven state linear model was identified based on the model structure derived in [72]. The model parameters were identified by using the prediction error method, which is a time domain identification approach. The PID design did not manage to suppress the coupling effect between the lateral and longitudinal motion of the helicopter and the flight controller was limited only to hover flight. Obtained results indicated that SISO techniques have moderate performance and that multivariable approaches are required to eliminate the inherent cross coupling effect of the helicopter dynamics. A similar multi-loop PID design has been implemented on a *Yamaha R-50* small-scale helicopter with shortcomings that restricted the autonomous flight of the helicopter only to hover mode [44].

Another simple classical control design composed of Proportional Derivative (PD) SISO feedback loops was investigated in [70] for the *Yamaha R-50* helicopter, the model of which was derived by using a frequency domain identification method. The identified helicopter dynamics were represented by a thirteen state linear model of the motion variables, the rotor and stabilizer bar characteristics. The identified linear model was then used for the optimization of the flight control system. In this particular case, the use of a notch filter was suggested for compensating the effect of the stabilizer bar on the helicopter's attitude dynamics. This approach indicated that although the performance of flight control systems based on classical control techniques was limited, accurate knowledge of the helicopter's model may significantly improve the design of the feedback loops.

However, the majority of linear flight controllers that have been applied to autonomous helicopter platforms, are based on the $\mathcal{H}_\infty$ feedback control approach. The $\mathcal{H}_\infty$ control scheme was initially introduced in [68]. The main advantage of the $\mathcal{H}_\infty$ approach, is its ability to cope with both model uncertainty and disturbance rejection. The $\mathcal{H}_\infty$ based controller design can be easily adjusted to classical control techniques and at the same time compensate for the multivariable effects of the helicopter. The work reported in [80] provides very strong arguments for why the $\mathcal{H}_\infty$ approach is a reasonable and suitable control solution for flight vehicles.

The typical structure of an $\mathcal{H}_\infty$ controller is composed of two parts. The first part is the loop shaping portion of the problem where the input channel is pre-compensated and post-compensated in a similar way that takes place in the classical control techniques of SISO systems. The pre-compensator includes Proportional Integral (PI) compensators for increasing the low-frequency gain of the system, disturbance rejection and attenuate the steady state error. The post compensator is typically used for noise elimination, therefore, it is typically composed of low pass filters. The second portion of the controller, is the $\mathcal{H}_\infty$ synthesis part, where a static feedback gain is calculated in order to stabilize the multivariable system dynamics, being also optimal with respect to a performance index. More about $\mathcal{H}_\infty$ control may be found in [12, 17, 78, 92, 113].

In [108] an observer based multivariable controller was designed using a singular value loop shaping method based on a two degree of freedom $\mathcal{H}_\infty$ optimization. The controller objective was the development of an Attitude-Command Attitude-Hold (ACAH) flight system for the full-scale Westland Lynx helicopter. Contrary to autonomous flight applications, the ACAH flight system is integrated with manned flight operations. The goal of the ACAH flight controller is for the helicopter to track an attitude and heave velocity command that is generated by the pilot's stick input. The principle of the controller design is to suppress the interaxis coupling of the helicopter dynamics, thus, decreasing the pilot's workload. The pilot is only charged with the generation of the reference attitude and heave velocity commands that are necessary for the helicopter's motion. The $\mathcal{H}_\infty$ controller design was based on an eight rigid body states and four actuator states linear model. The model was obtained by linearizing a more elaborate nonlinear model in hover mode. The controller performance was evaluated through flight simulations. Although the controller was designed for hover and low speed operations, the simulation results indicated satisfactory performance for speeds up to 90 knots.

Design of an ACAH flight system based on a static $\mathcal{H}_\infty$ loop shaping approach, is also reported in [83] for the Bell 205 full-scale helicopter. This work addresses the common problem that exists in multivariable modern control theory, according to which, the controller order is equal to the order of the plant to be controlled. This fact is of particular importance for the design of helicopter flight control systems, since the order of a full-scale helicopter model may reach up to thirty states! The order of the controller can be reduced by model reduction techniques, however, it is preferable to design from the beginning a flight controller of minimum order via the use of output feedback. When the complete state vector of a system is not available for feedback purposes, instead, only a subset of the state variables can be used by the controller; then the control law is classified as an output feedback controller. This research demonstrated the design of high performance and low order $\mathcal{H}_\infty$ controllers by applying linear matrix inequality optimization techniques. The helicopter model was derived by linearizing a thirty two states nonlinear model at hover. The linearized model was further truncated to twelve states by removing the dynamics associated with the main rotor. The performance of the developed ACAH system was tested in a series of helicopter maneuvers with satisfactory results.

An alternate $\mathcal{H}_\infty$ static output feedback controller design was proposed in [26–28] for the stabilization of an autonomous small-scale helicopter at hover. The output feedback approach allowed for the design of multivariable feedback loops using a reduced set of states that results in minimization of the flight controller's order. The structure of the proposed feedback loops reflects the physical flight intuition for helicopters such that the controller design was well suited for the particular application. The loop shaping part of the $\mathcal{H}_\infty$ controller attenuates the effects of helicopter high frequency unmodeled dynamics. In most cases, the output feedback controller design problem requires the solution of three nonlinear coupled matrix equations. In [26–28], a novel iterative algorithm was introduced that solved the $\mathcal{H}_\infty$ synthesis part of the controller by solving only two coupled matrix equations not requiring knowledge of an initial stabilizing gain. The controller structure is composed of two main loops. The first loop is responsible for the stabilization of the attitude dynamics while the second loop is used for position tracking. The controller design is based on a thirteen state linear model of the coupled fuselage and rotor dynamics. The model order and structure followed the approach in [70]. The identified parameter values were obtained for a small-scale *Raptor 90* radio controlled helicopter. The controller performance was evaluated by numeric simulations restricted to hover flights.

Promising flight results for an autonomous small-scale helicopter have been obtained in the work reported in [51, 53–55]. In this research, an $\mathcal{H}_\infty$ loop shaping controller was implemented on the Carnegie Mellon University's *Yamaha R-50*. This approach applied a blending of multivariable control techniques and system identification for the development of the flight control system. The helicopter nonlinear model is derived by using the MOdeling for flight Simulation and Control Analysis (MOSCA) modeling technique [52]. MOSCA combines first principles and system identification techniques for the derivation of both linear and nonlinear helicopter models. A thirty state nonlinear model was derived that includes the fuselage, main rotor, stabilizer bar and inflow dynamics. The helicopter nonlinear dynamics was further linearized in several linear models that correspond to certain operating conditions of the helicopter. Based on the multiple linear models a gain scheduled $\mathcal{H}_\infty$ loop shaping controller is applied.

Gain scheduling is a control technique according to which the gains of the controller vary depending on certain variables, called *scheduling variables*. The scheduling variables may be functions of the system's state variables or exogenous variables that describe the operating conditions of the system. The main design idea

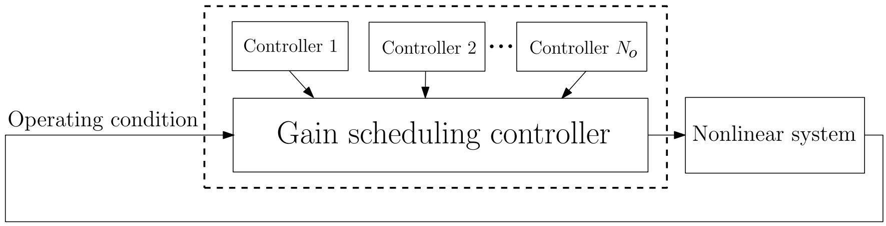

Fig. 2.2 Block diagram of a gain scheduling controller for a nonlinear system. The nonlinear system is linearized over N_o operating points. A linear controller is designed for each linearized model that corresponds to a particular operating point. The overall control law operates as an interpolator of the multiple linear controllers whose gain parameters depend on the operating condition of the nonlinear system

is to control a nonlinear system using a family of linear controllers. The nonlinear system dynamics are linearized over a finite number of operating points. The operating points are parametrized by the scheduling variables. For each linearized model that corresponds to a particular operating point, a linear controller is designed. The overall control law operates as an interpolator of the multiple linear controllers whose gain parameters depend on the scheduling variables. More details about gain scheduling may be found in [43, 87]. The gain scheduling approach has emerged from avionics control applications, where the linearization of the vehicle's nonlinear dynamics around several operating points is a rather common procedure. A descriptive block diagram of a gain scheduling controller for a nonlinear system is shown in Fig. 2.2.

An interesting comparative study between several controller designs is given in [109, 110]. Both classical and multivariable linear controllers are included in the study. An eighteen state linear model, which represents the helicopter dynamics at hover, has been used for the flight controllers design. The flight controllers were tested on an RC helicopter mounted on a mechanical structure that allows the motion of the helicopter in all directions of the Cartesian space. For hovering, multivariable techniques had superior performance in comparison with classical control designs. From the multivariable designs, LQR, $\mathcal{H}_2$ and $\mathcal{H}_\infty$ designs were evaluated. The flight validation indicated that in the multivariable design case it is preferable to design multiple feedback loops that correspond to independent subsystems of the helicopter dynamics, thus, decomposing the problem. This approach is preferable to design the controller for the complete helicopter dynamics. The low order subsystems should appeal to the physical flight intuition and should be as decoupled as possible. In the particular case the initial linear model was decomposed into a subsystem representing the longitudinal/lateral motion and a second subsystem of the heave and yaw dynamics.

An example of a linear controller design for a helicopter on a vertical stand is also given in [56]. The gimbaled like device on which the helicopter was connected to, allows only a three degrees of freedom motion of the latter. A discrete LQR is used with an augmented Kalman filter for state estimation. The work in [2] compares a simple eigenstructure assignment with full state feedback controller versus a typical

LQR design. The helicopter model under consideration does not include the flapping dynamics and the verification takes place by numerical simulations. Other robust designs of helicopter control are reported in [6, 50, 82, 97].

2.2 Nonlinear Controller Design

In general, most control designs have been/are based on linearized helicopter dynamics using the widely adopted concept of stability derivatives. However, in recent years there is considerable research related to helicopter flight control based on nonlinear dynamic representations. The nonlinear controller designs are mostly valued for their theoretical contribution to the helicopter flight control problem. Their applicability is still an open challenge mainly due to the increased order and nonlinear structure of the controller. However, their contribution to the understanding of the limitations and capabilities of the helicopter control problem is very significant.

Detailed models of helicopter nonlinear dynamics may be found in [40, 79, 84]. However, such models are of high order and impractical for controller design purposes. In [47, 48] a simplified nonlinear model of the helicopter dynamics is introduced. The helicopter model is represented by the nonlinear dynamic equations of motion of the helicopter enhanced by a simplified model of the aerodynamic force and torque generation. This particular model has been adopted in most research related to the helicopter nonlinear controller design. It indicates that exact input–output linearization fails to linearize the helicopter model resulting in unstable zero dynamics. It has also shown that the use of an approximate model that disregards the thrust forces produced by the main rotor flapping motion, is full state linearizable. This derivation is very important since, if the system dynamics are not input–output linearizable, most nonlinear control techniques would be inapplicable. A feedback linearization controller was proposed based on the approximated model dynamics. It was proven that the proposed controller, based on the approximated model, achieves bounded tracking of the position and yaw reference trajectories.

However, helicopters are characterized by significant parametric and model uncertainty due to the complicated aerodynamic nature of the thrust generation. Therefore, linearization and nonlinear terms cancellation techniques are poorly suited. It is important that the controller design exhibits sufficient robustness towards potentially significant uncertainty. A design that guarantees bounded tracking in the presence of parametric and model uncertainty is reported in [37]. The proposed control law incorporates stabilization techniques for feedforward systems with input saturation and adaptive nonlinear output regulation techniques.

The work reported in [66, 67] addresses the design of an autopilot for a helicopter capable of letting its vertical/lateral and longitudinal dynamics and yaw attitude dynamics tracking arbitrary references with only some bound requirements on the higher order time derivatives imposed by functional controllability. This work is an extension of [37], it includes the main rotor dynamics and allows for the tracking of arbitrary trajectories. In addition, the controller design is based on the pitch-roll-yaw attitude convention instead of quaternions, which are used in [37]. Similarly to [37], the final control structure is a mix of feedforward actions and nested saturation control laws. The controller in [66, 67] is able to enforce very aggressive maneuvers characterized by large attitude angles and to cope with possible large uncertainties affecting the physical parameters.

As previously mentioned, most nonlinear designs neglect the effect of thrust force components associated with the tilt of the main rotor disk. This is common practice since those parasitic forces have a minimal effect on translational dynamics. This simplification results in a set of system equations having a feedback form, which is ideal for backstepping control design established in [49]. Backstepping control implementation for helicopters is presented in [11, 21, 64, 65] and similar designs for a quadrotor in [32, 33, 42].

Approaches of nonlinear control that use Neural Networks (NN) and nonlinear inversion have been reported in [14, 15, 34, 38, 39, 45]. In all cases, the nonlinear inversion requirement and the augmentation of an NN increases significantly the order of the controller. To this extent, the derivation of the controller using the nonlinear equations of motion of the helicopter becomes impractical. Therefore, these cases have applied designed controllers based on the linearized dynamics of the helicopter around hover. In [34, 45] the analysis is even more restricted by using a simplified model of only the longitudinal and heave motion of the helicopter. In [38, 39] the controller was experimentally implemented to a *Yamaha R-50* helicopter for a simple step command response.

2.3 Remarks

This Chapter discussed several linear and nonlinear controller designs for helicopters. The focus of the presented approaches was emphasizing limitations and shortcomings of the corresponding designs, in an attempt to understand better what needs to be done in terms of controller designs to capture helicopter behavior executing aggressive and nonaggressive flights. Observations and results from this survey have been incorporated into the design concepts presented in subsequent Chapters.

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