Practical Survey on Design and Testing of Flight Control Laws for Helicopter Engineering Simulators

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Abstract: A practical survey on engineering implementation of flight control laws on helicopter engineering simulators is proposed. Advances of helicopter engineering simulators are introduced. Practical flight control technologies are reviewed, with an emphasis on discussing the corresponding engineering simulation programs. Finally, the difficulties of implementing advanced control technologies are addressed, and the future development of helicopter engineering simulators are highlighted.

Key words: helicopter; helicopter engineering simulator; flight control law; flight control technology

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0 Introduction

Helicopters have always aroused great interests and attention in the military and civil because of their unique capabilities of vertical take-off and landing, hover and forward flight. Large-scale helicopters are highly coupled, strong nonlinear, time-varying complicated systems, which have multiple flight modes, favorable maneuverability and low speed performances. These typical attributes bring to the helicopter flight control law (FCL) design a great deal of difficulties and tradeoffs. Moreover, a highly reliable FCL considerably improves helicopter's performance and stability for implementing their various properties safely and effectively, within its full flight envelop.

The development of flight control system (FCS) stimulates helicopter manufacture developing from its early beginning to its present stature, since helicopter stability and flying safety largely depend on the overall performance of FCS. Furthermore, the application of advanced flight control technologies directly contributes to the rapid development of engineering simulation platforms, which paves the way to practical implementations of advanced control theories.

Before real flight tests, it is very common to use flight simulator, not only to reduce time and costs, but also to protect pilots. With its flexibility, versatility and universality, flight simulator also enjoys great advantages on design and testing of flight control laws, making it an indispensable engineering tool in helicopter industry. Flight simulators are usually divided into training simulators, engineering simulators and research simulators[1]. The main function of training simulators is to provide aeronautical staff piloting skill to help them familiar with the real air vehicles via training transfer, and few engineering tasks are conducted on these facilities. In this paper, engineering simulators and research simulators are both defined as engineering simulators in that they are capable of exhibiting real time man-in-the-loop simulations to evaluate flight control laws, displays and human factors. Engineering simulators have been used by the aeronautics research community for many decades in developing

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and experimenting with advanced flight control concepts. Some of the well-known ground-based flight simulators that have capabilities for performing helicopter flight simulations are listed in Table 1.

With the advances in integrated digital processor and computer graphic imaging (CGI) technologies, ground-based flight simulator has found its legitimate role in man-in-the-loop applications, both as a research and development tool. Nevertheless, ground-based flight simulator reveals some limitations that rest in the incomplete nature of visual and motion cues. As a result, in-flight simulator has played an indispensable role in aerospace community, and it also provides a real flight environment for pilot training.

Helicopter in-flight simulators are often referred to as research helicopters. In order to deploy airborne simulations, these prototype helicopters are equipped with advanced avionics, FCS and sensor packages. Airborne simulation is an excellent tool for executing applied research assignments of handling qualities, control systems, displays, and human factors. Since 1990s, NASA keeps its leading position in the field of airborne simulation techniques, and various in-flight simulators (Table 2) have contributed to the development of airborne simulation till now.

Table 1 Helicopter ground-based flight simulators

Nation	Facility	Affiliation	Type
United States	FSAA[2]	NASA-Ames	Moving-base
	VMS[3]	NASA-Ames	Moving-base
	UAFDL[4]	University of Alabama	Fixed-base
Canada	UTIAS[5]	University of Toronto	Moving-base
	Merlin[6]	CAE	Moving-base
United Kingdom	LMS[7]	DERA	Moving-base
	HELIFLIGHT-R[8]	University of Liverpool	Moving-base
Germany	AVES[9]	DLR	Moving-base
	MPI Motion Simulator[10]	MPI for biological cybernetics	3-2-1 serial robot
Netherland	SIMONA[11]	TU Delft	Moving-base
France	SPHERE[12]	Eurocopter	Moving-base
China	Engineering Simulator[13]	AVIC China Helicopter R&D Institute	Moving-base

Table 2 Helicopter in-flight simulators

Nation	Facility	Affiliation	Prototype
United States	RASCAL[14]	Army/NASA	JUH-60A
	In-flight simulator[15]	Army/NASA	EH-60L
Canada	NAE airborne simulator[16]	NRCC	Bell 205-1A
Germany	ATTHeS[17]	DLR	BO-105
	ACT/FHS[18]	DLR	EC-135
France	Airborne simulator[19]	Eurocoper	Dauphine 6001

Both ground-based and in-flight simulators are indispensable research tools in testing helicopter flight control laws and evaluating handling qualities thus far. This paper presents a practical survey on the development of helicopter flight control technologies from a viewpoint of engineering implementation for the following reasons: (1) Subjective evaluation and design experience are obtained and accumulated from piloted simulations, providing insights to helicopter FCL design and testing; (2) only by implementing the advanced control technologies via engineering simulation platforms can verify the applicability of them; (3) gaps between advanced control methodologies and engineering applications can be identified so as to tailor FCL to helicopter performance specifications.

The next section presents an elaborate survey of practical flight control technologies in PID-based feedback control, explicit model following control and robust control. Specific engineering simulation examples are used from the literature. Core research questions are summarized and future developments of helicopter engineering simulation techniques are discussed in the last section.

1 Practical Flight Control Technologies for Helicopter Engineering Simulators

1.1 PID-based feedback control technology

In helicopter industry, PID-based feedback control method is the most fundamental one and has been widely used to design primary flight control laws for decades. Besides, PID-based feedback control also proved to be effective across various fixed and rotary wing platforms. The advantage of PID-based feedback control policy rests in the fact that without obtaining the full knowledge of helicopter aerodynamics, the desired dynamic response is achieved by tuning PID control gains manually against controller design specifications.

In 1990s, various FCL designs, with different level of controller complexity, were evaluated through a great deal of man-in-the-loop simulations, and the influence of FCL on helicopter flying handling qualities was addressed. Besides, quantities of engineering simulations of the advanced digital optical control system (ADOCS) program were conducted on vertical motion simulator (VMS) to investigate FCS concepts[3]. From 2004 to 2005, the CH-47F digital automatic flight control system (DAFCS) was tested on VMS in the degraded visual environment[20]. Applying scheduled SCAS gains, a newly developed FCL was tested on OH-58D in-flight simulator in 2011, resulting in improved handling qualities in the good visual environment (GVE) and degraded visual environment (DVE)[21].

In the ARH-70A R&D process, evaluations of the optimized PID FCL have been completed through both piloted simulations and in-flight tests. A system overview of the PID FCL design for ARH-70A is illustrated in Fig. 1. The PID FCL of ARH-70A is designed to track angular rate signals in pitch, roll and yaw axes. The reference commands p_c, q_c and r_c are generated by input filters and sensors are used to measure angular rates p, q and r. Variables K_P, K_I and K_D correspond to PID control gains with respect to each axis. The helicopter pitch/roll cross-coupling is eliminated using the mechanical mixer, and a saturation block is applied to prevent actuator activities from reaching saturation limit.

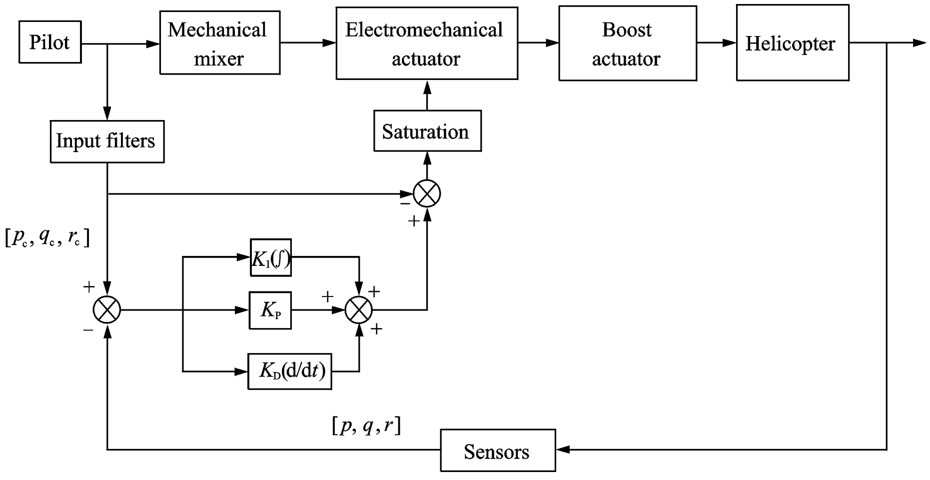


Fig. 1 Schematic of the PID control system for ARH-70A

Technically, the design and test of ARH-70A FCL are highlighted as a benchmark of how linear modeling, control gain optimization and piloted simulation can be integrated to make the optimum flight control law design against the requirement of a minimum amount of in-flight tests[22].

Applying the multi-objective parametric optimization tool set, the dynamic response of classical controllers has been improved more evidently than before, and there is no need to tune control gains manually. However, when PID-based feedback control approach is applied for multivariable, time-varying, highly coupled helicopter model, the expected controller performance is rather constrained, because some design specifications, e. g. high frequency dynamics, are not addressed.

1.2 Explicit model following control technology

Explicit model following control architecture is designed to make helicopter response follow desired dynamic response of command models. This flight control scheme is widely used in existing helicopter FCS, since it performs better command tracking and control decoupling capabilities.

In the beginning of 1990s, NASA-Ames applied the technology of explicit model following control to the Army′s ADOCS program to improve the handling qualities of the UH-60 helicopter[23]. After 2000, The Army/NASA rotorcraft aircrew systems concepts airborne laboratory (RASCAL) conducted an airborne simulation on testing explicit model following control laws using a JUH-60A Black Hawk research helicopter, which is equipped with a programmable high-bandwidth full-authority research FCS[14]. Besides, applying a frequency dependent feedback controller, a newly developed explicit model following control system was tested on development facility (DF)[24]. The explicit model following control system was also applied to the core automatic flight control system (CAFCS) in the RAH-66 Comanche[25].

As an enhanced version of standard explicit model following control architecture, modernized control laws (MCLAWS) were presented by Sikorsky Aircraft Corporation at the 21st century, under a national rotorcraft technology center project aims to upgrade the legacy control laws for helicopters that operate in DVE[26].

Fig. 2 shows the practical implementation of the MCLAWS into the UH-60 helicopter. As is shown in the control scheme, an explicit model following architecture is used to provide attitude command attitude hold(ACAH) control mode in pitch and roll axes. Specifically, ACAH means that the attitude of helicopter is proportional to pilot stick positions which are captured by linear variable differential transducer (LVDT) block. LVDT provides input signals to the command models

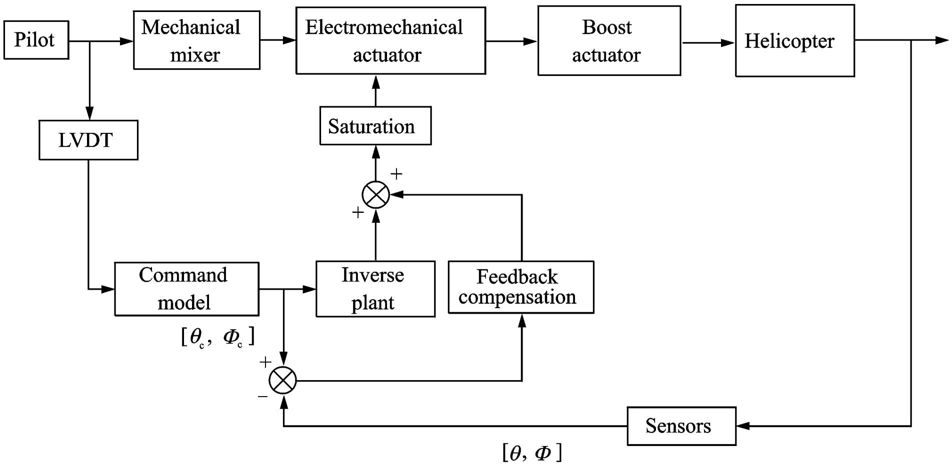
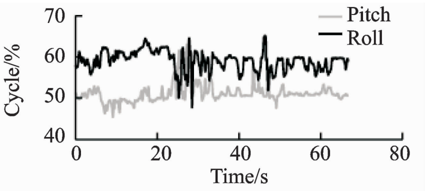


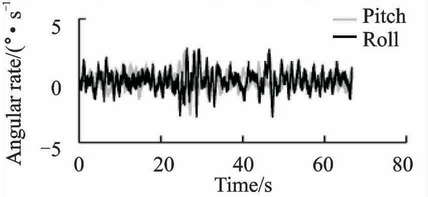
Fig. 2 MCLAWS control laws following the FCS architecture of UH-60

and they transform pilot inputs to desired pitch/roll attitude commands θ_c, $\boldsymbol{\Phi}_c$. Attitude signals, θ and $\boldsymbol{\Phi}$, are detected by vertical gyros. An inverse plant works to cancel the helicopter inherent dynamics. Disturbance rejection and plant stabilization are achieved using feedback compensation.

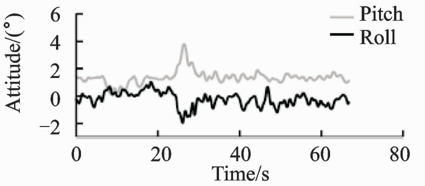
The MCLAWS architecture in Fig. 2 achieves an ACAH response type in hover conditions. In-flight tests were evaluated on UH-60 helicopter using the existing stability augmentation system (SAS) partial authority servos, and the real-time simulation results are shown in Fig. 3.



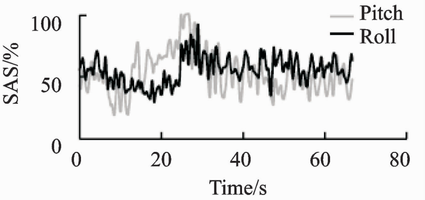
(a) Time history of cyclic pitch inputs



(b) Time history of angular rate responses



(c) Time history of attitude responses



(d) Time history of SAS servo responses

Fig. 3 In-flight tests for ADS-33 hover maneuver of UH-60[15]

In comparison with the legacy explicit model following control policy, MCLAWS has some unique characteristics: (1) Rate/attitude command models are generated; (2) the inverse plant is designed to eliminate helicopter's inherent modes; (3) disturbance rejection is achieved via feedback compensation, producing a transfer function of unity; (4) expected dynamic response is achieved using partial authority FCS.

The high level of modularity is provided from the enhanced explicit model following architecture, which contributes to the further development of engineering simulation programs. In 2003, simulation studies were conducted on VMS to evaluate MCLAWS, proving that improved handling qualities and reduced pilot workload are achieved in DVE[27]. In addition, man-in-the-loop simulations validated that MCLAWS achieved better performance than the baseline flight control law of UH-60A in the presence of wind turbulence. In 2005, MCLAWS was modified and tested on the EH-60L research helicopter for near-Earth operations in DVE[15]. With no parallel actuators, the modified MCLAWS architecture operates an ACAH flying mode using 10% SAS series servos, and a modern integrated tool set (SIMULINK®, CONDUIT®, CIFER®, etc.) is applied for controller designs. Subsequently, the engineering software package is widely adopted as a necessary tool for FCL designs of attack helicopter[28-29]. In 2007, a preliminary piloted simulation was conducted on the Camber AH-64D risk and cost reduction simulator (RACRS). The project is aimed to evaluate handling qualities in hover/low speed flight via MCLAWS, and requirements in ADS-33E for a DVE conditions are met by implementing three appropriate response types[28]. The second round of AH-64D MCLAWS evaluation was operated on the Boeing engineering development simulator (EDS). Control gains are optimized using CONDUIT®, and automatic flight mode transitions are implemented via a mode blending strategy which provides a more improved controller performance for AH-64D than using the standard MCLAWS. After 2011, the following-on FCL upgrades of UH-60 MCLAWS were identified over two rounds[30]. In 2016, the standard MCLAWS framework was augmented with an outer-loop position hold with velocity command mode to enhance helicopter flying handling qualities in DVE[31].

Engineering simulation experiments verify that perfect command tracking capabilities and desired decoupling performance are achieved using MCLAWS, but there still exists some practical shortcomings of this control approach: (1) The performance of the low-order linear inverse plant is rather limited, since it is time-invariant and incapable to vary with velocity-dependent dynamics; (2) unknown rotor dynamics and neglected structural modes increase the controller sensitiveness to system uncertainties. In this case, robust control strategies are required to augment the legacy control architecture to improve robustness properties and to guarantee desired controller performances.

1.3 Robust control technology

Robust control methods can be regarded as an online strategy capable of regulating systems whose dynamics contain uncertainties. Moreover, robust controller provides better robust stability than the explicit model following control against neglected and unmodeled dynamics.

Numerous robust design approaches, such as LQR[32], LQG/LTR[33] and H_∞[34], have been studied extensively. In coping with control problems of highly nonlinear, coupled aerial vehicles, H_∞ has proven to be an effective control strategy, since it allows the control system engineer to address stability, performance and robustness properties in the design of FCL. By selecting frequency dependent weights, H_∞ optimal control approach is used to minimize the infinity norm of weighting functions while achieving important frequency domain properties. This design process is often referred to as loop shaping. The coprime factor based loop shaping approach is designed to capture a certain degree of robust stability and to achieve close-loop stability across the frequency domain of interest. A block diagram of H_∞ controller with coprime factorization is provided in Fig. 4, where the plant is coprime factored as $M^{-1}N$, with coprime factors, ΔN and ΔM.

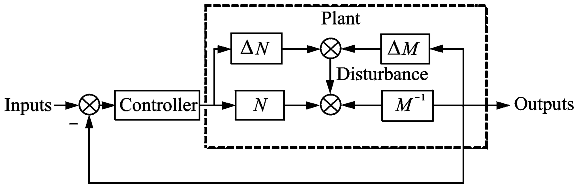


Fig. 4 Block diagram of H_∞ control against coprime factors

Three advantages indicate that this coprime factorization based H_∞ controller method is superior to standard H_∞ control: (1) The input-output properties remain invariant; (2) right half plane poles can be canceled out; (3) the solution of compensators is guaranteed against robustness specifications.

In 1998, the coprime factor based H_∞ control method was successfully applied to a research helicopter, the National Research Council of Canada′s (NRCC) Bell 205 helicopter[7,16]. In order to implement an ACAH flight mode in hover and low speed, University of Leicester designed an H_∞ controller against coprime factor uncertainties using a loop shaping procedure. According to Fig. 5, the static feedback controller K is obtained by solving the H_∞ optimization problem

$$\left\| \begin{bmatrix} K \\ I \end{bmatrix} (I + W_2 G W_1 K)^{-1} M^{-1} \right\|_\infty \leqslant \gamma \qquad (1)$$

where the optimal index γ is small enough. The final feedback controller K_∞ is then constructed using the static output feedback controller K with compensators W_1 and W_2 such that $K_\infty = W_1 K W_2$.

In addition, the large motion system (LMS) simulator was used to conduct ground-based tests and the Bell 205 airborne simulator was used to evaluate controller performance in real flight. In-flight simulation results are shown in Fig. 6, verifying the effectiveness of H_∞ FCL for a helicopter attitude tracking control.

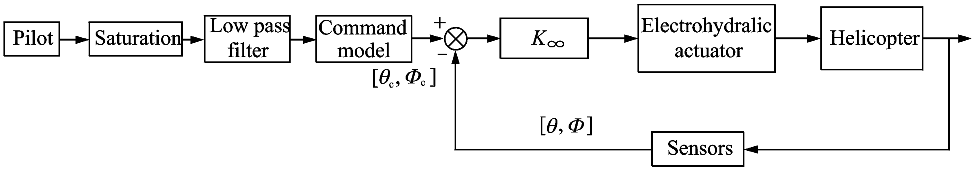
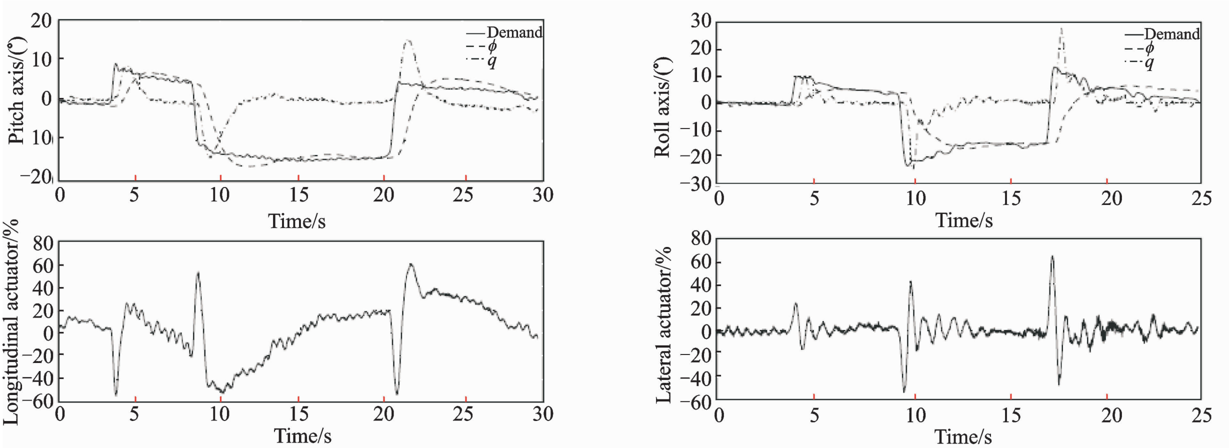


Fig. 5 Block diagram of H_∞ FCS for Bell 205



(a) Pitch axis response to longitudinal cyclic step inputs

(b) Roll axis response to lateral cyclic step inputs

Fig. 6 In-flight tests of Bell 205 H_∞ flight control laws for ACAH response type[16]

These pilot simulations are highlighted as a benchmark in the practical application of H_∞ control approach. Robustness stability is guaranteed and positive pilot evaluations are provided on flying the H_∞ controlled system. Moreover, the continuing engineering simulation of multivariable H_∞ control policy makes tremendous efforts to close the gap between advanced robust control theory and practical implementation. Nevertheless, some drawbacks still impair the H_∞ controller performance. One is the slow dynamic response. Another one is that H_∞ method causes large undershot of non-minimum-phase system for normal acceleration tracking control. Additionally, suboptimal solutions of control gains have to be adopted, since optimal control gains obtained from Gamma iteration have difficulties in engineering application because of their large magnitudes.

To compensate for these deficiencies in dynamic performance of a H_∞ controller, H_2 control strategy is often adopted to augment the standard H_∞ controller. Therefore, a mixed H_2/H_∞ control strategy is proposed. In recent years, a number of H_2/H_∞ controller designs are used to solve aerospace problems[35-40], but few of them have been verified through engineering simulations.

Using measurements of the slung load states, Rigsby et al[41]. designed a H_2/H_∞ robust feedback controller for helicopters handling external loads. The Sikorsky simulation facility executed the mission of evaluating controller performance, indicating that the approach is very efficient in decreasing external load swing[42]. Moreover, the novel controller denotes mission-oriented specifications for FCL designs, and brings inspiration on helicopter performance evaluations as well.

Apparently, both H_∞ and H_2/H_∞ are linear control methods, which utilize the common concept of linear modeling, the stability derivatives. The main shortcoming of linear modeling originates from the assumptions of small deviations from trim points. However, these assumptions cannot be guaranteed at all circumstances, resulting in gain scheduling, mode switch, and non-unitary controller performance. Thus, nonlinear control technologies will help to address the conservativeness of linear control and to understand nonlinear helicopter dynamics.

In general, nonlinear control methodologies are valued for the theoretical contributions to helicopter flight control problems. The practicability of nonlinear controller designs is an open challenge due to the higher-order and nonlinear nature of the controller[43].

Nonlinear dynamic inversion (NDI) control strategy has been studied for decades. The NDI method is designed to generate a control input via feedback control and state transformation such that, when it is used to the nonlinear plant, the linear relation between virtual control inputs and plant outputs is obtained[44]. However, NDI requires exact nonlinear cancellation to achieve expected performance, resulting in controller's high sensitivity to system uncertainties, and the drawback stimulates the development of incremental nonlinear dynamic inversion (INDI)[45].

In 2016, Boeing Mesa initiated a cooperative program with TU Delft on developing advanced flight control laws for AH-64D helicopter. Significant contributions are addressed through the design and testing phase of INDI FCL[11]. The INDI control architecture implements an rate command (RC) mode using Apache's limited authority setting (Fig. 7). Instead of using the nominal virtual input to compute the complete control input, it is possible to determine only the required variation Δu with respect to the previous inputs. In order to form the required command signals, a unit delay block is used to access the current control input value u_0. Another advantage is that the implementation of INDI is based on the onboard measurements of state accelerations without acquiring the state-dependent part of the plant, and there is no need to obtain an accurate knowledge of the model.

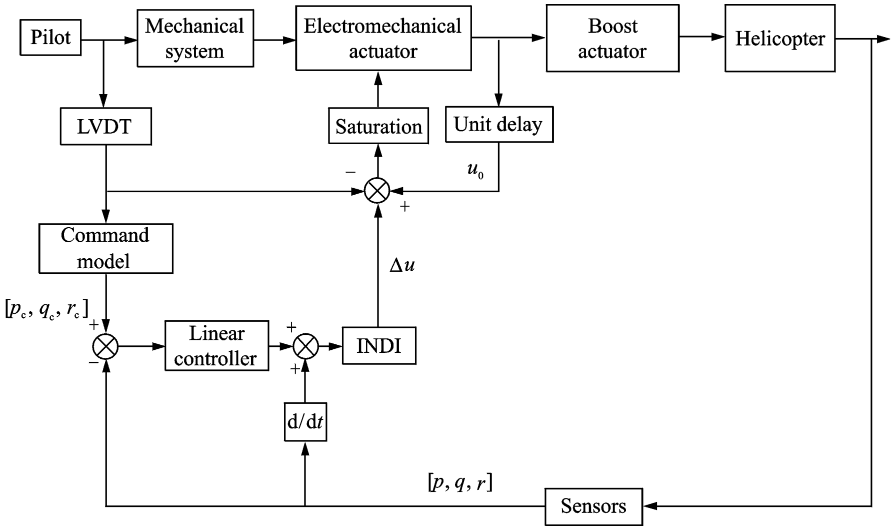


Fig. 7 Implementation of RC mode into AH-64's INDI control architecture

Piloted real-time simulations are conducted on the SIMONA research simulator in GVE and DVE conditions. The experimental results of handling quality ratings indicate that INDI FCL reduces the pilot workload compared with the AH-64's legacy FCL, and improves the helicopter flight performance operating in DVE conditions. Furthermore, the INDI control approach has also been used to solve flight control problems across various aerial platforms[46-51], indicating that the nonlinear controller design provides enormous potential for future application in existing helicopters and other aerial vehicles.

2 Discussion and Conclusions

Helicopter engineering simulators are invaluable tools for design and testing of flight control laws, and they have significantly facilitated ongoing helicopter engineering simulation programs. The application of helicopter flight control laws is determined by several aspects, such as control theory, flight safety concerns and simulation platforms. In this case, only a limited number of controller designs are realizable when practical implementations of actual helicopter FCS are taken into account. The realization of advanced control technologies still confronts with some roadblocks of demonstrating a feasible helicopter FCL implementation, and the further investigation is being conducted to incorporate the following aspects:

(1) Non-affine control inputs

The nonlinear helicopter system is not affine in control inputs, which causes unwanted controller response if actuator and main-rotor dynamics are considered. With Taylor series expansion, incremental control policy provides insights in how to make the nonlinear system depend affinely on control inputs. However, neglected high-order terms lead to imprecise model reduction, and cause significant amounts of conservatism in coping with unmodeled high frequency dynamics. Therefore, controller designs that directly account for non-affine nonlinear plant would be more attractive than those that are based on partial linearization or model transformation.

(2) Multiple time-varying state variables

Helicopter is a highly complicated time-varying system with various states variables[52]. In order to design a reliable state feedback FCS, high-performance sensors are required to feedback state signals. However, the extensive use of sensors not only introduces sensor noise and bias, but also results in excessive designs of compensators. To implement state feedback control architecture, observers are used to reconstruct states using available sensors. The commonly used Kalman filter-type observer requires that the controlled system be minimum phase, and on the other hand, full-order observer degrades controller's robust stability. Therefore, a novel sensor-based control policy, augmented with reduced-order observers, will provide the possibility to make a better tradeoff between sensor configuration and observer designs.

(3) Dynamic cross-coupling effects

Strong dynamic coupling effect makes the helicopter FCL design challenging, since each control input not only affects the state variables of interest, but also produces unintended secondary responses. There still exists an obvious gap between simulations of off-axis response and helicopter flight test data[53]. Future investigations conducted on the discrepancy would help to provide enlightenment on controller design approaches that aim to minimize the cross-coupling response of a helicopter operation in highly flexible maneuvers and in multimode transitions.

To sum up, the prospective research on advanced control technologies (nonlinear model predictive control, fault tolerant control, etc.) is expected to shed more practical light on engineering simulation programs. Besides, the mechanical layout of ground-based engineering simulator tends to become more sophisticated, which is capable to perform more complicated flight maneuvers. Furthermore, newly devised in-flight simulators are suitable to equip with high-bandwidth control system, data acquisition package and integrated avionics, permitting more actual representation of airborne dynamic performance and providing enlightenment on FCL implementations as well.

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