Active Stick Controllers for Fly-by-Wire Helicopters – Operational Requirements and Technical Design Parameters

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Fly-by-Wire systems are about to replace conventional control systems also in helicopters. Consequently new kinds of cockpit controllers, in particular electrically actuated "active" systems permitting commanded movements of the control stick, get into focus of research.
These active stick controllers could improve situational awareness of the cockpit crew through tactile feedback of primary flight parameters, co-pilot / autopilot actions, and flight envelope limits.
This paper presents examples of requirements imposed on such a stick system by mission, aviation aspects, premises on cockpit philosophy, and regulations and standards.
The identification and discussion of technical questions on the design of this stick system as well as an ample consideration of factors possibly influencing the choice of parameters constitutes the main part of the research that has been carried out, a brief overview of which is given here. Primary aspects are input–output principle, feedback variable, characteristic curve of feedback, bandwidth, and coupling of sticks among each other and with the autopilot.

1 Introduction

This paper presents an outline of the research conducted in the frame of a final study thesis [1] of the first author at the Institute of Airborne Systems.

Several recent publications [2, 3, 4, 5, 6, 7] examine actuated cockpit control elements for primary flight control, so-called active stick controllers (or inceptors). While this research considers, in most cases, mainly technical aspects of such a design, the goal of the research described herein is to give a more general view on the operational requirements in a helicopter environment (like in [8]) and to identify and discuss how this operational side is influenced by the possible choices of technical parameters and vice versa.

2 Helicopter Handling Qualities and Human Factors

2.1 Reasoning for Fly-By-Wire Systems

Flight mechanics of a helicopter is characterised by several coupling effects: a control input is not only translated into a movement with respect to the intended axis but also into rotations around and movements into the direction of the other axes. At the same time a helicopter is naturally unstable in at least the phugoid motion and, depending on the configuration, in other modes during hover flight. A third hurdle to easy handling are various boundaries and avoid zones in the flight envelope like "dead man's curve", vortex ring state, retreating blade stall etc.

For acceptable handling qualities and a high overall mission capability of the aircraft–pilot entity, these shortcomings must be addressed. For this task Stability Augmentation Systems are current state of the art but fly-by-wire systems are probably the first-choice technology in this domain since further arguments known from fixed-wing aviation, such as weight-savings, reduced maintenance volume and increased safety, are valid for helicopters as well.

To date, apart from prototypes and technology demonstrators, one helicopter in service – the European NH90 transport helicopter – is equipped with a fly-by-wire system; one version of the American Sikorsky S-92 currently under development will feature this technology and further examples are likely to emerge.

2.2 Need for New Controller Types

With the advent of fly-by-wire (FBW) systems in the helicopter cockpit, new questions on design of its controllers are raised. Since it is then no longer a function of stick controllers to transfer forces, these controllers can be seen as input devices which provide a command interface to the flight control system. These "passive" cockpit controllers are state of the art for FBW aircrafts such as the Airbus types. However, they entail reduced situational awareness through the loss of direct feedback of control inputs.

Over recent years, new technologies and concepts in the cockpit have unburdened the pilot from several tasks and converted his duty mainly to system management. However, new work load was generated and the new systems made the task of system surveillance more demanding and mission complexity and mission time could be extended. Most of the information transfer attributed to these tasks is conducted via the visual channel which can become one of the bottle necks of modern flight crew performance. It is therefore highly desirable to use other human senses to convey information – for stick controllers this is the tactile perception.

2.3 Tactile Feedback

The idea of tactile feedback via the controllers is to improve situational awareness of the cockpit crew by providing specific information about one or several parameters' states. This parameter (feedback variable) should be chosen to assure particular awareness of:

- Attitude and other primary flight parameters
- Execution of intended commands
- Inputs made by co-pilot
- Autopilot's commands
- Flight envelope limits and avoid zones

To transfer this information, controllers have to be capable of being actuated; these "active" controllers form an entirely new field of research in aircraft systems.

3 Requirements and Design Goals for Active Controllers

Active controllers, as a sophisticated and vital part of the aircraft's avionics, face stringent constraints from several sides. This begins with regulations and standards that have to be adopted in most cases to cope with active controllers and partially extended to set the framework for completely new issues.

Like other systems, active controllers have to fulfil mission related requirements, conditions from aviation and ergonomics / human factors aspects, and premises on cockpit philosophy as well as "classical" requirements like minimised mass, volume, and direct and indirect cost.

For example, behaviour in case of failure and degradation, especially loss of the active functionality, is a particularly important subject. The system has to be designed either to assure the availability of the active sub-system at a high enough level (e. g. $P(\text{loss}/h) < 10^{-7}$) or to include a passive back-up system for stick feel and damping.

Active cockpit controllers offer the potential to provide a highly innovative interface for the crew; however this unconventional behaviour could generate an elevated need for type rating training and could inhibit cross-type rating. An operator-imposed requirement subsequently could call for preserved commonality with existing helicopter types when new specific features are implemented.

4 Design Parameters

Being an innovative development, various basic technical parameters of an active stick controller have to be considered closely. Apart from these discussed in more detail below, there are:

- Secondary feedback (stick shaker-like warnings)
- Dynamic properties (behaviour with respect to pilot induced oscillation)
- Ergonomics (location of pivotal points, control forces etc.)
- Combination of axes: integration of yaw axis control in the right-hand stick

4.1 Input–Output Principle

One basic choice when designing an active controller is which of its two state variables, deflection and interface force between hand and stick, should be used as the input variable that is fed forward to the flight control system. The other, being the output variable, provides the tactile feedback interface.

The other major parameter is the relation between the input and output variable. If the output value is determined only by the independent external feedback variable, like roll angle, there is no direct relation between input and output per se and the system is called "unbound active". Systems determining the output value as a function of the input value are termed “bound active systems” consequently.

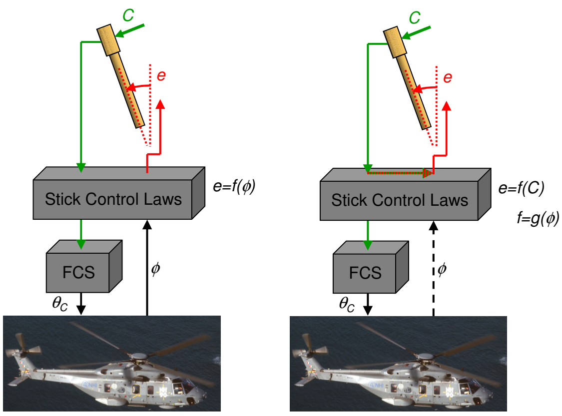
The four possible combinations of these two parameters represent the different input–output principles (IOPs)

- force input–displacement output (FIG. 1(a))
- displacement input–force output
- force input–displacement modulation (FIG. 1(b))
- displacement input–force modulation.

4.2 IOP–Response Type–Feedback Variable

With unbound active systems, for each axis the respective feedback variable, which is mapped onto the output variable, has to be chosen. In conjunction with the IOP and the response type of the flight control laws, this choice has far-reaching implications for the characteristics of the human–machine interface.

Given the lapse of the applied lateral input force and the possible feedback variables cyclic blade pitch angle, bank angle, heading, rate of yaw, rate of roll, and their derivatives over time for a steady turn (FIG. 2), the questions arising in the context of IOP, feedback variable, and response type become clear: When force input–displacement output is chosen for the system, the stick remains rigid (isometric behaviour) as long as the flight parameter chosen to determine the output variable has not changed. For displacement input–force output, no resistance is felt during the first period (isotonicity) until a feedback force builds up in parallel to the respective feedback variable.



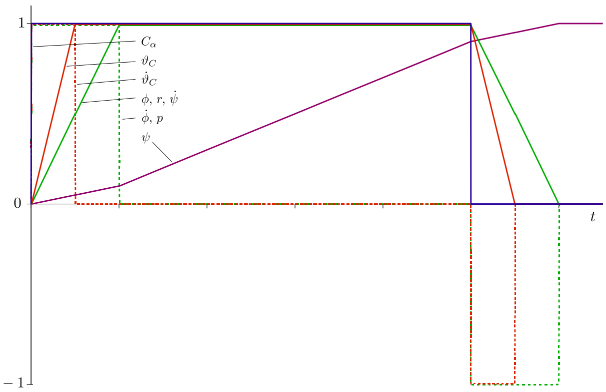
(a) Unbound active system. (b) Bound active system.

Figure 1: Schematics of the two classes of input–output principles.

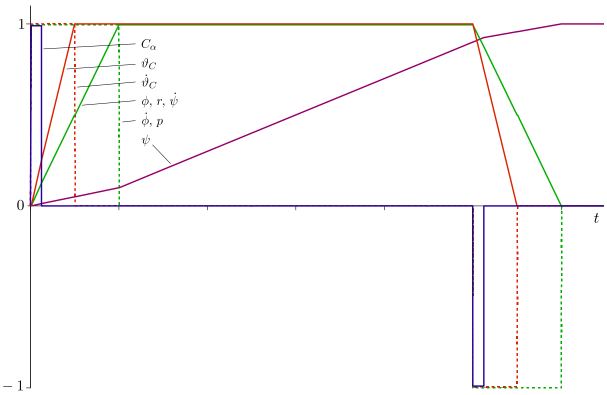
FIG. 2(a) and FIG. 2(b) also illustrate the influence of the response type in this context: An attitude response type of the helicopter flight control system, meaning that a given input results in a proportional attitude relative to the respective axis (e. g. $C_\alpha \propto \phi$), leads to completely different handling characteristics of the stick controller than a rate response type, where the input is proportional to the related angular velocity of the helicopter (e. g. $C_\alpha \propto p$).

4.3 Characteristic Curve of Feedback

Bound active controllers can be described as behaving like classical spring–damper systems augmented by the capability of providing a freely



(a) Attitude response type.



(b) Rate response type.

Figure 2: Normalised graphs of lateral input force (C_α), cyclic blade pitch angle (ϑ_C), bank angle (ϕ), heading (ψ), rate of yaw (r), rate of roll (p), and their derivatives over time for a steady turn. Note time gap between build-up / drop-off of input (C_α) and possible feedback variables (all others).

shaped and adaptable characteristic curve (Fig. 3), which represents the relation between stick deflection and control force.

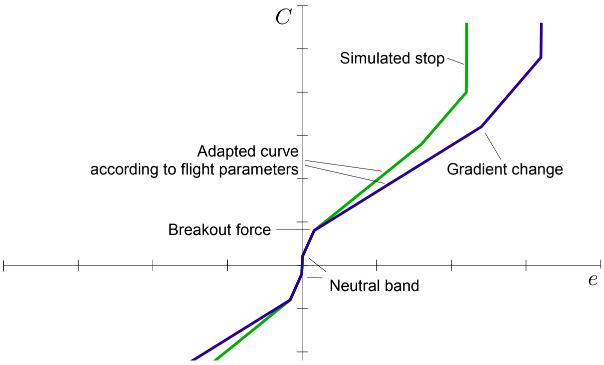


Figure 3: Exemplary characteristic curve of feedback of a stick controller with features offered by active functionality.

Here, the role of the feedback variable only is to provide a secondary parameter in function of which the characteristic curve can be adapted. A simple example is the increase of input force necessary to obtain a certain bank angle with increasing forward airspeed.

A possible, more sophisticated utilisation of this adaptability is to announce the approach to avoid zones in the flight envelope or reducing margins to its boundaries by a change of force gradients of the characteristic curve of feedback.

4.4 Bandwidth

The global transmission bandwidth of the system, that is the band of frequencies resolved and transmitted by the stick system, is both a factor of cost and crucial for proper operational performance, so the requirements on this property have to be examined thoroughly.

Demand for a high bandwidth comes from characteristics like haptic quality for the operator, rigour of simulated stops, abruptness of gradient changes in the characteristic curve, minimal simulated apparent inertia of the stick, and secondary feedback.

Factors determining the bandwidth are sampling frequency of sensors, clock rate of computers, bus cycle times, and mechanical properties (inertia, play, friction, elasticity).

5 Cockpit Cross-Coupling and Autopilot Coupling

Unbound active systems feed back information about the related feedback variable; the source of the variable's variation being irrelevant. Co-pilot and autopilot inputs are therefore returned to the stick controller implicitly, whereas for bound active systems a dedicated function has to provide cockpit cross-coupling and autopilot coupling into the feedback mechanism. Variants of this "virtual shaft" connecting the two sticks and the autopilot include totally rigid (Fig. 4) and variably flexible principles.

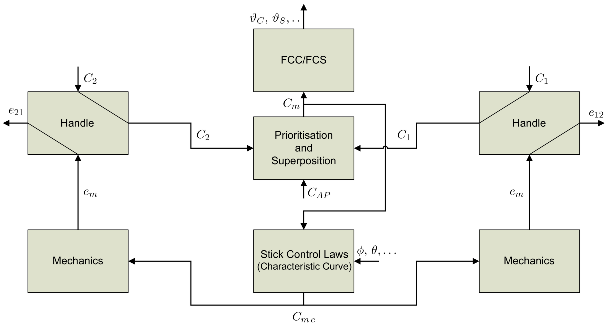


Figure 4: "Rigid virtual shaft", one example of a principle to couple two stick controllers and the autopilot.

6 Conclusion and Outlook

Many of the issues identified in the work presented here showed to need more detailed consideration to clarify their interaction, and their consequences on the interface characteristics in particular. One subsequent step surely has to be practical evaluation in a ground simulator and in a flying simulator to gain experience on questions like optimal IOP and its relation with helicopter handling qualities in a realistic environment.

Having these findings at hand, the clear evaluation of parameters and their interaction, together with a prioritisation of requirements, can then serve as a starting basis for a final stick controller specification.

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A comprehensive compilation of literature relevant to the subject is included in [1].