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COFCLUO

Clearance of Flight Control Laws using Optimisation

1.4 Aeronautics and Space

D1.0.6 Progress report M30 WP1

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Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

1 Technical Overview

1.1 Summary of the specific objectives

The reporting period covers months 25-30 of the project. The specific objectives of WP1 in the reporting period are summarized below:

- finalization of the development of LFT-based models
- development of preliminary software for generation of parametric models

1.2 Overview of technical progress up to month 30

1.2.1 Work Package 1.1 – Integral Nonlinear Modelling

Involved partners: AIRBUS (Responsible)

Work package objectives: The first objective of this work package is to provide models for developing and testing the techniques studied and developed in Work Package 2. The developed models need to be representative for a civil commercial aircraft, taking into account nonlinearities along with the most complete description of dynamics available (rigid and structural dynamics). A flight control law to serve for clearance purposes is also provided. A second objective is to define the clearance problem for a civil aircraft to serve as basis for the robustness analysis studies within the COFCLUO Project.

This work package has been successfully terminated (Month 12), but several updates of the software have been performed, for example, developing a version for Linux needed to fulfil WP2.2 or providing an improved flight control law to serve for analysis purposes. Two aircraft models have been developed: a rigid-body *nonlinear dynamics model*, and an *integral model*, represented by a set of linearized models with both rigid and flexible modes. These models are used by the analysis teams in WP2 to solve clearance problems for the selected criteria.

1.2.2 Work Package 1.2 – Clearance Criteria

Involved partners: LIU, AIRBUS, DLR (Responsible), FOI, ONERA, UNISI

Work package objectives: The objective of this work package is to define a representative set of clearance criteria which are considered most relevant for the clearance of a civil aircraft (e.g., stability and handling quality related, but also criteria related to actuator damage due to fatigue). Both linear model based and non-linear model based criteria will be considered. For each criterion, the corresponding trim conditions are defined together with the description of relevant parametric uncertainties. The main outcome of the activities in this work package is a criteria library containing the clearance criteria to be used in the optimisation driven worst-case search based clearance.

This work package has been successfully terminated (Month 12) without any deviation from the project work programme. All partners are committed to contribute to continuously extend this library during the whole duration of the COFCLUO project by adding new functions for the criteria used by each analysis team. The last update of the library was performed by including three new criteria for nonlinear analysis implemented by DLR.

1.2.3 Work Package 1.3 – Trimming and Linearization

Involved partners: DLR (Responsible), ONERA

Work package objectives: The objective of this work package is to develop fast and reliable trimming and linearization tools necessary for the optimisation-based clearance of flight control laws. To ease the trimming and linearization, the implementation of a specialised user-friendly aircraft trimming tool is envisaged, with capabilities like the easy selection of trimming options, support for generation of good initial guesses, and code generation (for embedded trimming).

This work package has been successfully terminated (Month 12) without any deviation from the project work programme. The developed tools have been employed within WP1.4 for the generation of LFT-models for nonlinear aircraft dynamics.

1.2.4 Work Package 1.4 – LFT Modelling

Involved partners: LIU (Responsible), DLR, ONERA

Work package objectives: The objective of this work-package is to develop algorithms for generation of Linear Fractional Transformation (LFT) models, from linearizations of the non-linear model and from the linerized models of the integral model. These models are crucial for the convex programming approaches to optimisation in WP2, resulting from linear criteria and models and from convex relaxations of non-linear criteria and/or models. The challenge is to develop low-order rational approximations of Linear Parameter-Varying (LPV) models that result from the linearization and to give accurate estimates of the resulting approximation error. Special attention will be given to modelling of structural dynamics. A complete LFT-model of the aircraft linear dynamics and their dependencies on parametric uncertainties will be developed. Moreover, tools based on LFT-models and identification techniques will be developed and used in order to study the sensitivity of flight control laws with respect to parametric uncertainties in order to reduce the size of the LFT.

Progress towards objectives: The objectives in this work package have been addressed in two distinct activities.

The **first activity** is the generation of LFT-models and represents the main work in this work package. The associated Deliverable 1.4.7 describes the development of several LFT models to be used by the analysis teams in WP2. The developed LFR models for the nonlinear aircraft model address the uncertainty modelling in the longitudinal axis aircraft model and in the corresponding longitudinal control laws over the whole flight envelope. Similar LFR models have been also developed for the integral models. The development of the LFR models have been performed closely following the needs of the analysis teams. Recently, following a request of the University of Siena, it was decided to prepare a similar set of LFR for the lateral aircraft dynamics. In what follows, we give a short account of main achievements.

As decided during the status meeting on February 12-13, 2009, in Stockholm, firstly the generation of LFT models for the longitudinal nonlinear aircraft dynamics has been pursued by DLR, in order to be coupled to the already available LFT model for the longitudinal controller of the aircraft developed by ONERA. The goal was to obtain an LFT-model of the closed-loop system along the longitudinal axis which can be used immediately by the analysis teams. The first LFT models for the longitudinal A/C model have shown poor behaviour when coupled with the controller for the nonlinear longitudinal A/C model. Therefore, some enhancements of the A/C LFT-models was necessary to improve their accuracy. This was achieved partly by employing a finer grid in both parameter space and flight envelope (almost three times denser than for that used for the previous LFT-models), and partly by generating “local” LFT models, which are valid only on certain subdomains of the flight envelope. The resulted 16 local LFT models, each of order 120, cover the whole uncertainty domain corresponding to different Mach number, calibrated air speed, weight and position of center of gravity. The achieved overall accuracy is significantly better (3-4 times) than for the previous generation of LFT models. Additionally, LFT-models of the actuators and the sensors have been provided.

Note: Two additional LFRs will be developed for the lateral part of the nonlinear controller (M30/31) by ONERA as well as additional closed-loop LFRs for the lateral part of the nonlinear model (M31) jointly by ONERA and DLR.

Open-loop LFRs for both the longitudinal and the lateral part of the integral model have been generated by ONERA. For both longitudinal and lateral motion there exist two sets of LFRs: one for a frequency range up to 50Hz and the other one for a reduced frequency range up to 15Hz. For each frequency range, seven subsets of LFRs with increasing complexity in the uncertainty/parameter-block exist (center tank, outer+center tank, payload+outer+center tank, mach+airspeed, center tank+mach+airspeed, outer+center tank+mach+airspeed, payload+outer+center tank+mach+airspeed). For each subset, an LFRs for stability analysis and for comfort analysis have been developed.

The LFT models of the longitudinal axis controller over the complete flight envelope have been generated by ONERA in the previous reporting period. However, since the size of the initial controller LFTmodel was deemed to be too high when compared with the size of the LFT model of the nonlinear aircraft model, it was decided to generate new LFT models with possibly lower sizes to fit also with the partitioning of the flight envelope used to generate the nonlinear aircraft LFTs. The resulting new LFT models have significantly smaller sizes, leading to closed-loop LFT models of manageable sizes for the analysis teams. The LFT models of the actuators have been slightly modified by ONERA so as to represent the rate limiters and the saturations by deadzone nonlinearities instead of sectors. Note that for the moment, efforts are underway to generate an LFT-model for the lateral controller as well, in order to obtain an LFT-model of the closed-loop system along the lateral axis. Appropriate MATLAB scripts have been implemented to automate the generation of various closed-loop LFRs.

In summary, the following LFRs have been generated by DLR and ONERA since the beginning of the project:

a) Nonlinear Model:
- Two open-loop LFRs for the global nonlinear model (DLR)
- Sixteen open-loop LFRs for the longitudinal part of the nonlinear model (DLR)
- Sixteen open-loop LFRs for the lateral part of the nonlinear model (DLR)
- Three LFRs for the longitudinal part of the nonlinear controller (ONERA)
- Closed-loop LFRs for the longitudinal part of the nonlinear model (ONERA, DLR).

b) Integral Model:
- Open-loop LFRs for both the longitudinal and the lateral part of the integral model (ONERA). For each subset of configuration and flight condition, an LFR for stability analysis and thirteen LFRs for comfort analysis exist.
- One LFR for the longitudinal part of the controller for the integral model (ONERA)
- Closed-loop LFRs for the longitudinal part of the integral model (ONERA).

The **second activity** consists of developing new approximation methods and software for generation of LPV models and is performed mainly by LIU. The achievements of this activity are documented in several already finished Deliverables 1.4.1-1.4.4. The Deliverable 1.4.5, with deadline July 31, 2009, should describe the development of final software for generation of LPV models. However, due to Daniel Petersson's (LIU) paternity leave this activity cannot be presumably finished on time and therefore will be delayed. The proposed new date to finish this deliverable D1.4.5 is October 31, 2009.

1.3 Status of deliverables

Del. No.	Deliverable name	Work package No.	Date due	Actual/ Forecast delivery date	Estimated person-months	Used person-months	Lead contractor
D1.4.4	Preliminary software developed	WP1.4	Month 24	Month 24	10 LIU:10	7 LIU:7	LIU
D1.4.5	Final software developed	WP1.4	Month 30	Month 30	10 LIU:10	9.5 LIU:9.5	LIU
D1.0.6	Progress report M24 WP1	WP1.0	Month 30	Month 30	0.1 DLR	0.1 DLR	DLR
D1.4.7	Preliminary LFT models for nonlinear behaviour and complete model of aircraft linear dynamics	WP1.4	Month 18	Month 18	16 DLR:6 ONERA:10	17 DLR:7 ONERA:10	ONERA

Table 1. List of deliverables.

Note: ONERA's work (3PMs) foreseen in Deliverable D1.4.3 was moved to D1.4.7 and was supplemented with 2PMs. All these are now included in the estimated and performed PMs on D1.4.7.

1.4 Status of milestones

No milestones in the reporting period.

1.5 Planned activities in the next 6 months

In the next 6 months the following activities are planned:

- Preparation of a final report on the determination of LPV models (D1.4.6)

2 Management and coordination aspects

The expected delay in producing Deliverable 1.4.5 will have no practical consequences, because this activity is completely independent of the rest of the project and no one else depends on this deliverable.

During the Stockholm meeting, it was decided to perform the LFT modelling also for the lateral controller in order to allow the University of Siena to perform its analysis. The contribution of ONERA to deliverable D1.4.7 was hence increased by 2 PMs from 8 to 10 where one month stems from ONERA's COFCLUO budget and the other one stems from LIU which will transfer 1 PM to ONERA.

3 Plan for using and disseminating the knowledge

Exploitable knowledge and its use: The developed preliminary LFT-models are presently used by the analysis teams to produce the final results of the project.

Dissemination of knowledge: On the project web-site all deliverables with dissemination level public are published. The address is http://er-projects.gf.liu.se/~COFCLUO.

Publishable results: The results reported in D1.4.7 on the generation of LFT-models for the integral model have been presented at ROCOND'09 in the paper: *Generation of flexible aircraft LFT models for robustness analysis*, by Clément Roos from ONERA. These results as well as similar ones on generation of the rigid body LFT-models will be presented at the final COFCLUO Workshop in Stockholm to be held at the termination of the project.