AST5-CT-2006-030768

COFCLUO

Clearance of Flight Control Laws using Optimisation

Specific Targeted Research Project

1.4 Aeronautics and Space

Publishable final activity report

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Duration: January 31, 2010

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Revision 0.1

1 Project execution

1.1 Background

Proving to the certification authorities that an aircraft is safe to fly is a long and complicated process. It is the responsibility of the manufacturer to show that the aircraft complies with the certification specifications, and especially the so-called airworthiness code. This code contains a huge amount of different criteria that has to be met. Before manned flights are performed to show that an aircraft meets all the clearance criteria, simulations and computer computations are performed. This project has focused on the computer computations in the certification process. If the computations can be made faster, time is saved which will reduce time to market for new products and will also allow for rapid prototyping. Moreover, it is also desirable to make the computations more detailed and accurate which will improve the quality of the certification process, and thus increase the safety of aircraft.

1.2 Objectives

It is important to keep in mind that the questions addressed in this project are not purely technical, since industry is already technically able to successfully clear flight control laws. The main industrial benefits of the new methods should be related to reducing the involved effort and cost, while getting sufficiently reliable results, or increasing the reliability of the analysis results with a reasonable amount of effort. Therefore a benchmark problem has been defined according to current industrial standards and the results obtained from optimisation-based clearance have been compared with a baseline traditional solution based on gridding the parameter space and testing the flight control laws for a finite number of manoeuvres. The clearance criteria have been selected so that the successful use of them in conjunction with optimisation-based CFCL will result in fewer off-line and manned simulations.

1.3 Work performed

The work performed in the project has been carried out in three different work packages, one for modelling, one for optimization, and one for evaluation. Below more information are given for each work package separately.

1.3.1 Modelling

This work package was dedicated to develop suitable parametric models to serve for aircraft clearance purposes and related software tools to support various modeling activities. The basic aircraft models describe the dynamics of a generic two engines civil aircraft and serves primarily for simulation and structural modes analysis purposes. The provided flight controller covers both the normal as well as peripheral flight envelope. For implementing different clearance criteria for a range of optimization-based approaches, different types of parametric models were needed to be employed. A non-linear dynamics aircraft model with explicit parametric dependencies has been developed together with appropriate flight control laws to be cleared. Also so-called integral linear models depending on relevant parameters have been provided to model flexible aircraft configurations. A criteria library has been defined and implemented starting from the specifications of the benchmark problem for both the integral linearized as well as non-linear closed-loop aircraft models. The availability of reliable, accurate and fast trimming and linearization tools was essential for generating linearized models. Such tools have been developed and served for efficient and accurate criteria evaluations in optimization-based worst-case search. The trimming and linearization tools have been also used to obtain parameter dependent linearized models (so-called LPV models), which can be alternatively described using linear fractional transformation (LFT) based representation of system matrices. LFT-based models for the closed-loop aircraft models (both nonlinear and integral models) have been generated to serve for analysis purposes. While most of the work has been carried out during the first year, the LPV-modeling and LFT-generation activities have been pursued practically during the whole project period by improving successively the quality of approximations, developing new LPV-approximation methods and generating LFT- models of lower complexity. In what follows we describe in more details the main achievements obtained.

1.3.1.1 Integral nonlinear modeling

The models used for flight control laws design are mainly linear reduced order models which take into account only the rigid aircraft dynamics. Therefore, the validity of the resulting controllers (usually also linear) is restricted to constant flight conditions around the chosen trimming/linearization points. However, the real operation of an aircraft is very different. Aircraft have generally a complex nonlinear dynamics (e.g., non-linear aerodynamic coefficients, presence of structural dynamics), operates in widely varying conditions (altitude, speed, temperature, payload distribution), and are potentially subject to inputs of large magnitudes (deflection of surfaces, strong turbulence gusts). The present tendency to build larger and larger aircraft, for which the structural dynamics have a significant influence on aircraft motion, brings an additional complexity level into analysis and design by the associated high order aircraft dynamics and high order FCL. This explains why the complexity of flight control laws used nowadays for civil aircraft control and of the associated control logic is continuously increasing. Such control laws express complex non-linear dependencies which describe various flight control tasks like gain scheduling, switching between different gains, coping with actuator limitations, activating appropriate protection functions, etc. In the same time, the tendency is to build wider and wider aircraft for which the structural dynamics have an impact on aircraft motion.

The main objectives of the modeling work were to provide dynamical models of a civil aircraft as required by the analysis techniques studied and developed in the. 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. The developed models are representative for a civil commercial aircraft and take into account all relevant nonlinearities along with the most complete description of dynamics available (rigid and structural dynamics). The models also include models of actuator and sensor dynamics. A flight control law for normal and protected flight operations used for clearance purposes has been also provided.

1.3.1.2 Clearance criteria

The objective was to define a representative set of clearance criteria which are considered most relevant for the clearance of a civil aircraft. Both linear model based and non-linear model based criteria have been considered. The defined criteria covers the assessment of stability, handling quality, turbulence caused loads, or non-exceedance of protection limits (see Table 1, where the criteria covered by different analysis teams in the COFCLUO project can be seen). For each criterion, the necessary evaluation model, the employed indicators, and the criterion definition and evaluation procedure are described. Additionally the corresponding trim conditions have been defined together with the description of relevant parametric uncertainties. The main outcome of the activities in this work package is a criteria library containing MATLAB scripts implementing the clearance criteria to be used in the optimisation driven worst-case search based clearance.

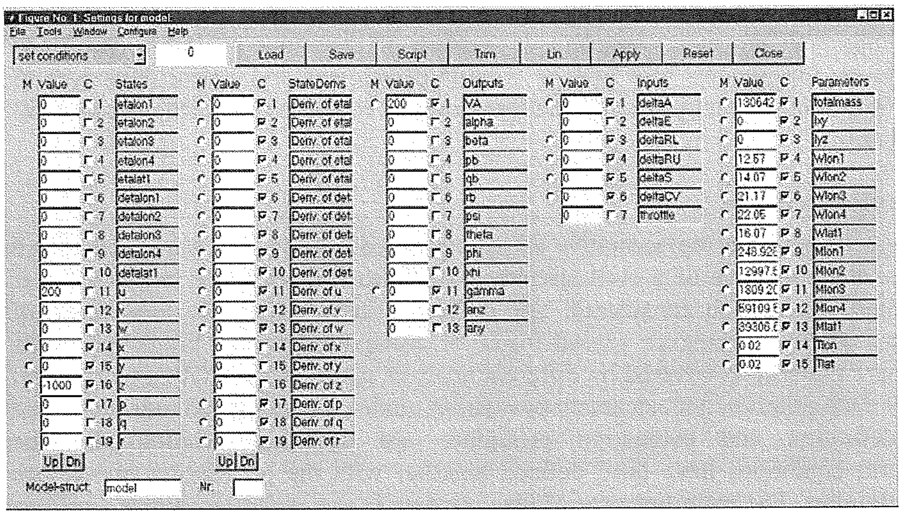
Criteria types	Criteria names / (#)	Model(s)	LIU	DLR	UNISI	ONERA	FOI
Stability	**Eigenvalues**	**NLS, LIM**	✓		✓	✓	
	Stability margin	**NLS, LIM**				✓	
	Nonlinear stability	**NLS**		✓	✓		
Handling	**Manoeuvrability (2)**	**NLS**		✓			
Loads	**Turbulence/Comfort**	**LIM**	✓		✓		
	Manoeuvre	**LIM**					
Protections	**Maximum normal acceleration (2)**	**NLS**		✓			
	Maximum/minimum pitch angle (2)	**NLS**		✓			
	Maximum angle of attack	**NLS**		✓			
Worst-case pilot input		**NLS**					✓

NLS - *Nonlinear simulation model;*
LIM - *Linear integral model*

Table 1: Clearance criteria addressed in the COFCLUO project

1.3.1.3 Trimming and linearization

The objective was to develop fast and accurate trimming and linearization tools necessary for the optimization-based clearance of flight control laws. To ease the trimming and linearization, a graphical user interface (GUI) (see Fig. 1) has been implemented to allow an user-friendly aircraft trimming, with capabilities like the easy selection of trimming options, support for generation of good initial guesses, and code generation (for embedded trimming). This GUI relies on the fast and accurate numerical trimming tools based on nonlinear system and nonlinear least-squares solvers.



0

M	Value	C		States
	0	☐	1	etalon1
	0	☐	2	etalon2
	0	☐	3	etalon3
	0	☐	4	etalon4
	0	☐	5	etalat1
	0	☐	6	detalon1
	0	☐	7	detalon2
	0	☐	8	detalon3
	0	☐	9	detalon4
	0	☐	10	detalat1
	200	☐	11	u
	0	☐	12	v
	0	☐	13	w
○	0	☑	14	x
○	0	☑	15	y
○	-1000	☑	16	z
	0	☐	17	p
	0	☐	18	q
	0	☐	19	r

M	Value	C		StateDerivs
○	0	☑	1	Deriv. of etal
○	0	☑	2	Deriv. of etal
○	0	☑	3	Deriv. of etal
○	0	☑	4	Deriv. of etal
○	0	☑	5	Deriv. of etal
○	0	☑	6	Deriv. of det
○	0	☑	7	Deriv. of det
○	0	☑	8	Deriv. of det
○	0	☑	9	Deriv. of det
○	0	☑	10	Deriv. of det
○	0	☑	11	Deriv. of u
○	0	☑	12	Deriv. of v
○	0	☑	13	Deriv. of w
	0	☐	14	Deriv. of x
	0	☐	15	Deriv. of y
	0	☐	16	Deriv. of z
○	0	☑	17	Deriv. of p
○	0	☑	18	Deriv. of q
○	0	☑	19	Deriv. of r

M	Value	C		Outputs
○	200	☑	1	VA
	0	☐	2	alpha
	0	☐	3	beta
	0	☐	4	pb
	0	☐	5	qb
	0	☐	6	rb
	0	☐	7	psi
	0	☐	8	theta
	0	☐	9	phi
	0	☐	10	chi
○	0	☑	11	gamma
	0	☐	12	anz
	0	☐	13	any

M	Value	C		Inputs
○	0	☑	1	deltaA
	0	☐	2	deltaE
○	0	☑	3	deltaRL
○	0	☑	4	deltaRU
○	0	☑	5	deltaS
○	0	☑	6	deltaCY
	0	☐	7	throttle

M	Value	C		Parameters
○	130642	☑	1	totalmass
○	0	☑	2	Ixy
○	0	☑	3	Iyz
○	12.57	☑	4	Wlon1
○	14.07	☑	5	Wlon2
○	21.17	☑	6	Wlon3
○	22.05	☑	7	Wlon4
○	16.07	☑	8	Wlat1
○	248.92	☑	9	Mlon1
○	12997.	☑	10	Mlon2
○	1809.2	☑	11	Mlon3
○	59109	☑	12	Mlon4
○	39306.	☑	13	Mlat1
○	0.02	☑	14	Tlon
○	0.02	☑	15	Tlat

Model-struct: model
Nr.:

Fig. 1 Graphical user interface for aircraft trimming

The improved accuracy of the new trimming tools can be observed by the significantly increased coverage (green marked areas) of the flight envelope which can be observed when comparing Figures 2 and 3.

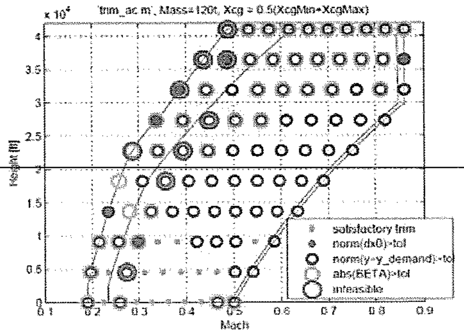


Figure 2: Trim results obtained with the original trimming tools. The line within the flight envelope indicates the minimum selectable speed values for a given altitude.

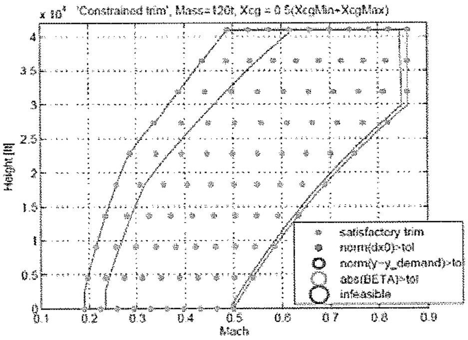


Figure 3: Trim results obtained with the enhanced trimming tools. The line within the flight envelope indicates the minimum selectable speed values for a given altitude.

1.3.1.4 LFT modelling

The objective was to develop algorithms for generation of Linear Fractional Transformation (LFT) models, from trimming and linearization of the non-linear model. These models are crucial for the convex programming approaches to optimization for CFCL, 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 has been given to the modeling of structural dynamics. A complete LFT-model of the aircraft linear dynamics and their dependencies on parametric uncertainties has been developed. Moreover, tools based on LFT-models and LPV-identification techniques have been 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.

A first activity was the generation of LFT-models to be used by the analysis teams. The developed LFT models for the nonlinear aircraft model address the uncertainty modeling in the longitudinal axis aircraft model and in the corresponding longitudinal control laws over the whole flight envelope. Similar LFT models have been also developed for the integral models. The development of the LFT models have been performed closely following the needs of the analysis teams and lasted practically the whole duration of the project. In what follows, we give a short account of main achievements.

Firstly the generation of LFT models for the longitudinal nonlinear aircraft dynamics has been pursued in order to be coupled with the LFT model of the longitudinal controller of the aircraft. 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 showed poor behavior 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 sub-domains 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. Two additional LFT models have been developed for the lateral part of the nonlinear controller as well as additional LFT models of the closed-loop global nonlinear model to support stability analysis and turn coordination criteria.

A whole methodology has been proposed to convert a set of aeroelastic models into LFTs. It can be applied to any kind of purely numerical models for which the analytical structure is unknown. A preprocessing step first generates reduced models with consistent state space matrices and accurate modal/frequential content. A basis of multivariate orthogonal functions is then defined and a polynomial interpolation is performed. The structured tree decomposition is finally applied to build an LFT. An efficient algorithm is also proposed, which allows to select only the most relevant monomials during the interpolation step and thus to prevent data over-fitting. This significantly reduces the LFT complexity while maintaining a satisfactory accuracy. The application of this methodology to the integral aircraft model has proven conclusive. The resulting LFT are indeed highly representative of the plant behavior, in the sense that their eigenvalues and frequency responses almost exactly match those of the initial models at the considered grid points (see figure 4). Moreover, the trajectories of their eigenvalues and the continuum of their frequency responses remain quite regular on the whole continuous parametric domain (see figures 5 and 6). It should finally be underlined that their reasonable complexity makes them exploitable for analysis purposes.

Two sets of open-loop LFTs have been generated for both the longitudinal and the lateral part of the integral aircraft model: one for a frequency range up to 50 rad/s and the other one for a reduced frequency range up to 15 rad/s. For each frequency range, seven subsets of LFTs with increasing complexity in the uncertainty/parameter block exist. For each subset, an LFT for stability analysis and 13 LFTs for comfort analysis have been developed.

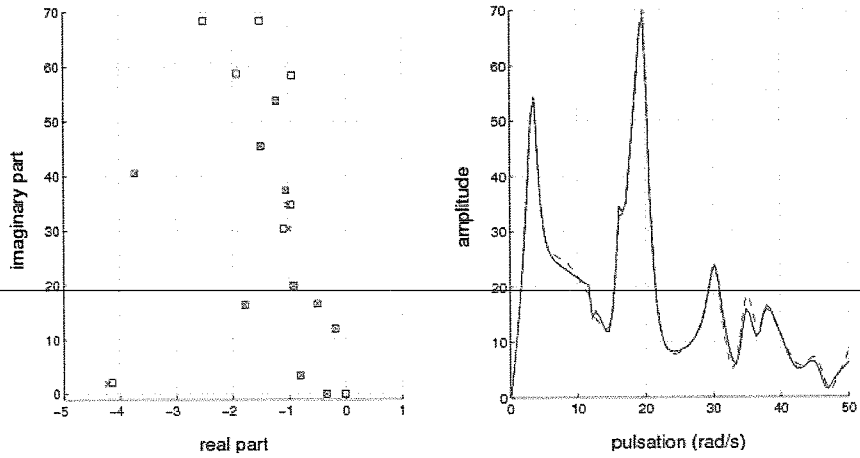


Figure 4: Comparison of eigenvalues (left) and frequency responses (right) on the grid (squares and solid lines: reference models - crosses and dashed lines: LFT)

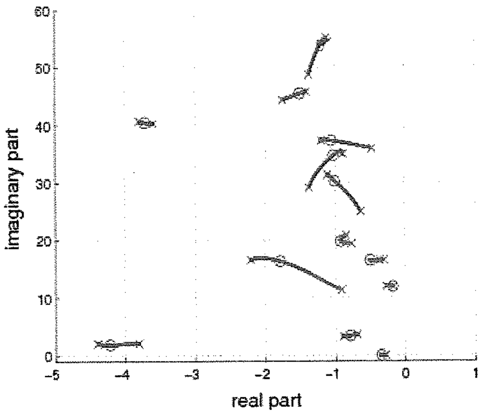


Figure 5: Modal trajectories (crosses and circles: reference models)

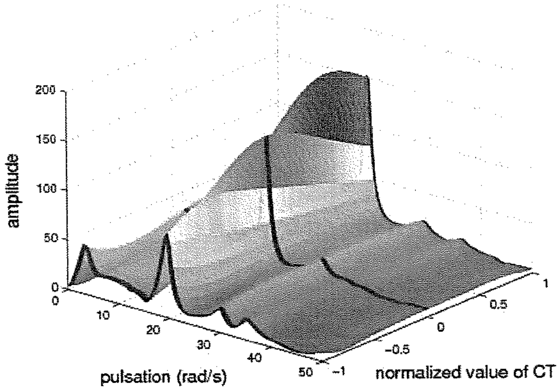


Figure 6: Frequency response continuum (solid lines: reference models)

The LFT models of the longitudinal axis controller over the complete flight envelope have been generated using the block-diagram structure of the initial nonlinear controller. Each block is replaced by its LFT counterpart (scheduled gains, position saturations and rate limitations, nonlinearities like tabulations, deadzones, ...). The interest of this approach is that, after the modification of one controller element, the user just needs to change this block and does not have to regenerate the complete LFT model of the overall controller.

However, since the size of the initial controller LFT model 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. Two LFT-models for the lateral controller were also generated, in order to obtain an LFT-model of the closed-loop system along the lateral axis.

The second activity was development of new methods for LPV-identification. It was originally a side track to develop new methods and theory for LPV-identification and LFT-generation, with the hope to apply the new methods to the models in the project. A new method was developed and improved during the project. This method was also tested on the existing models with good result.

The original idea was to find a new method that uses optimization and tries to capture important system properties and alleviate some of the drawbacks that existing methods have, such as failure to handle the case when there are different states in different models, which is the case in the integral models delivered by Airbus. This was done by formulating an optimization problem which directly optimized an input-output discrepancy between the identified model and the given data. Some new methods were developed and tested, and one of them was selected to be the most promising. This method was in the beginning of the project very slow, but during the project the algorithm has been sped up several orders of magnitude and was finally applied to realistically sized models.

The method was, during the last 12 months, tested on LFTs delivered by ONERA in the purpose of reducing the size of the LFTs. The reduction was successfully performed and the size of the LFTs was reduced substantially with high accuracy. This is an important step to do before the analysis because this will speed up the analysis step, in some cases from 9 hours to 5 minutes. Models reduced with this method have been used at the University of Siena to speed up their analysis step and the quality of the results has been consistent with the original models.

1.3.2 Optimization

Several different techniques were developed to address clearance of flight control laws (CFCL). They can be grouped in two different categories:

1. Sufficient techniques based on solving convex optimization problems and using LFR models of the aircraft
2. Necessary techniques based on solving nonlinear optimization problems and using standard nonlinear differential equation models of the aircraft

In the first category LFT models have to be developed and then convex optimization problems are solved. In case the method delivers a positive answer, it is for sure known that the whole region of the flight envelope and the whole region of uncertain parameters considered are cleared. However, if the method delivers a negative answer, nothing is known, i.e. it could be the case that the region considered is safe, but the method was not able to provide that answer. Therefore the methods in this category are conservative, i.e. they are so-called sufficient techniques for CFCL. Also the methods might provide the wrong answer in case the LFR models do not approximate the nonlinear differential equations of the aircraft accurately enough.

In the second category no LFT models need to be developed. In case a method finds a violation of a clearance criteria, it is for sure known that there is a point in the flight envelope which is not cleared. In case the optimization algorithm is able to find the global optimum at least one unsafe point in a region that has unsafe points will be found. This is the reason why this category of methods are called necessary techniques for CFCL. However, solving nonlinear optimization problems is difficult, and often only local optima are found. Because of this, it may happen that these methods fail to find unsafe points. Hence, in general, if the method cannot find un unsafe point, usually nothing is known, i.e. it could be the case that the regions considered are not safe because the method has missed an unsafe point, or the region is safe because there are no unsafe points.

Because of what has been said above the two different categories of methods are complementary to one another. In case a method in category 1 cannot say anything for sure, it could be that a method in category 2 may detect an unsafe point. Also in case a method in category 2 cannot say anything for sure, it could be the case that a method in category 1 can clear the whole region under consideration. Of course it can also be the case that methods from both categories employed together cannot say anything for sure. Notice that it should never be possible for a method in category 1 to clear a region at the same time as a method in category 2 finds an unsafe point, unless the LFT models do not approximate the nonlinear differential equations accurately enough. This fact can be used to validate the LFT models.

1.3.2.1 Survey of existing methods

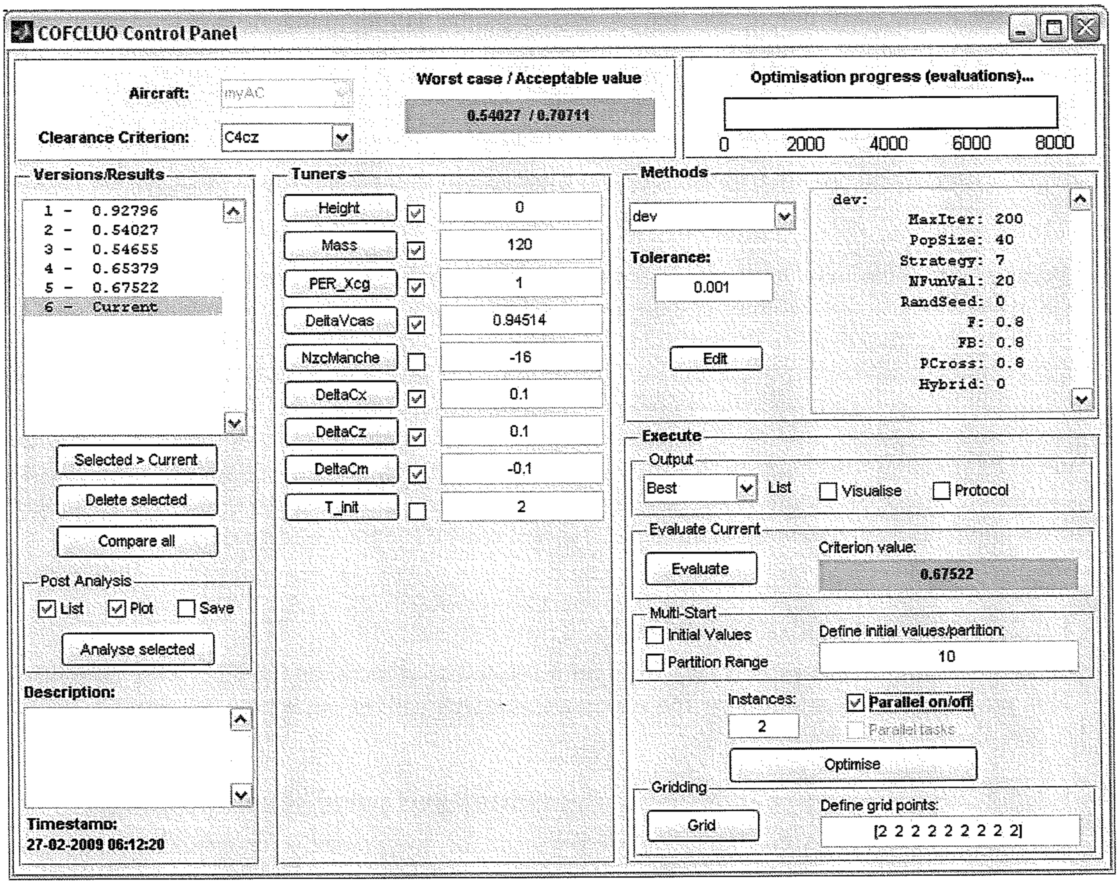
In the beginning of the project existing optimization based methods for CFL were reviewed. This provided the foundation for the continued research carried out within the project, which is described in more detail below.

1.3.2.2 Non-linear programming algorithms and parallel computation

The clearance problem of flight control laws can be formulated as a robustness analysis problem, where a set of suitably defined clearance criteria must be checked to lie within certain limits for all admissible variations of aircraft parameters, pilot inputs and all flight conditions. The idea of non-linear programming for flight control law clearance is to use available and efficient optimization methods to find those parameters/flight conditions for which the criteria are violated or poorly satisfied. Eight selected clearance criteria have been fully analyzed using the worst-case search based approach. The addressed simulation-based clearance problems cover stability, manoeuvrability and protections criteria.

The final goal was to develop a flexible and user-friendly prototype software tool which allows the use of both local and global optimisation in combination with parallel computation techniques to determine worst-case parameter/flight condition combinations. To this end the following work was performed:

- Translation of a set of representative flight control law clearance problems into simulation-based objective functions for optimisation,
- Investigation and enhancement of global search algorithms,
- Development of a clearance strategy based on global search that assures detection of worst cases with a prescribed confidence level,
- Building up a flexible prototype clearance tool including mechanisms for parallel computation based on a proprietary optimisation tool,
- Testing and verification of the tool,
- Benchmarking the flexibility of the tool by introducing other simulation models and/or criteria.



Aircraft: myAC

Clearance Criterion: C4cz

Worst case / Acceptable value 0.54027 / 0.70711

```
1 -  0.92796
2 -  0.54027
3 -  0.54655
4 -  0.65379
5 -  0.67522
6 -  Current
```

☑ List ☑ Plot ☐ Save

Timestamp: 27-02-2009 06:12:20

Height	☑	0
Mass	☑	120
PER_Xcg	☑	1
DeltaVcas	☑	0.94514
NzcManche	☐	-16
DeltaCx	☑	0.1
DeltaCz	☑	0.1
DeltaCm	☑	-0.1
T_init	☐	2

dev

Tolerance: 0.001

```
dev:
     MaxIter: 200
     PopSize: 40
    Strategy: 7
     NFunVal: 20
    RandSeed: 0
           F: 0.8
          FB: 0.8
      PCross: 0.8
      Hybrid: 0
```

Best List ☐ Visualise ☐ Protocol

Criterion value: 0.67522

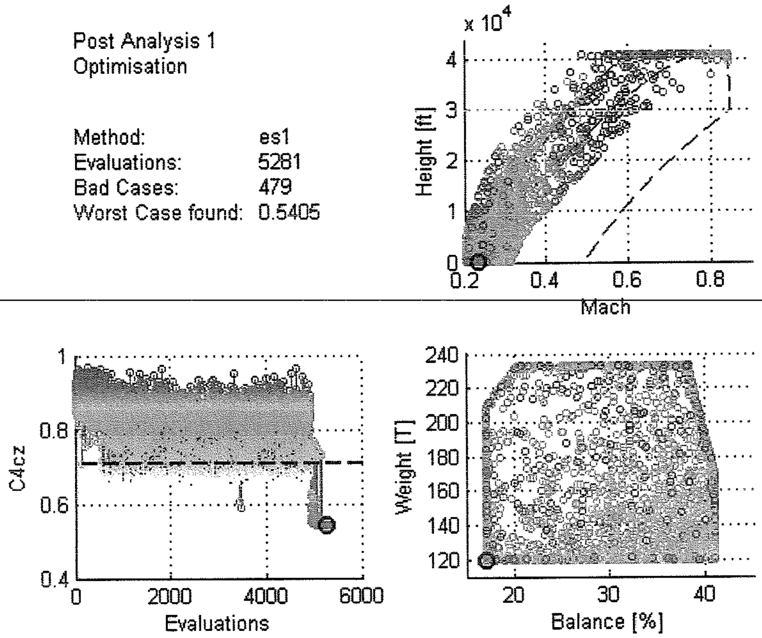
☐ Initial Values ☐ Partition Range

Define initial values/partition: 10

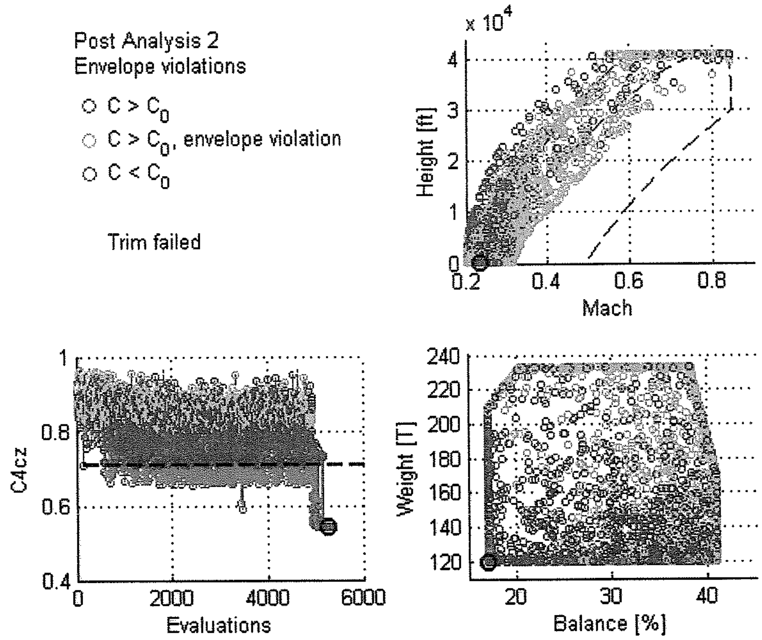
Instances: 2 ☑ **Parallel on/off**

Define grid points: [2 2 2 2 2 2 2 2 2]

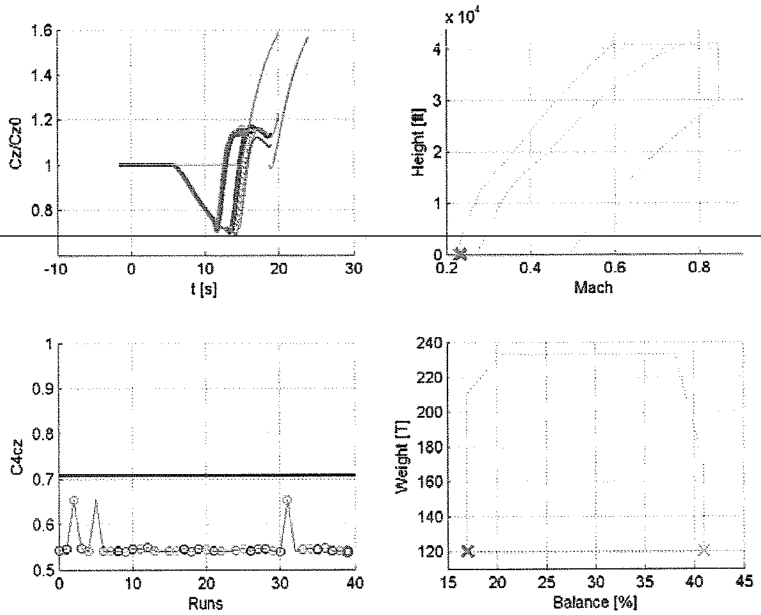
Above is shown the control panel of the COFCLUO worst case search software tool. It controls: criterion selection, result (version) management, post analysis, optimisation parameters (Tuners), method selection and parameters, output, multi-start optimisation and parallel computation. In addition raster computation is possible for comparison reasons.


Post Analysis 1
Optimisation

Method:	es1
Evaluations:	5281
Bad Cases:	479
Worst Case found:	0.5405


Post Analysis 2
Envelope violations

In the figures above are shown visualisation results of a single global optimization run with more than 5000 evaluations. The diagrams on the right show the distribution of the trial points in the parameter space. The diagrams on the left show the progress of the criterion value during optimization. In the upper diagrams the colour of the entry points is correlated with the criterion value. Entry points of the lower diagrams are grouped according different properties of the result: Satisfactory ($C>C_0$) or unsatisfactory ($C<C_0$) behaviour with or without violation of protection bounds. Trial points where trimming or numerical simulation failed are marked extra.



Above a visualisation of the result of 40 independent optimisation runs is shown: In 37 instances the worst case was found successfully. Only 3 runs terminated early in a local minimum at maximum balance but with criterion value still below the clearance bound. Corresponding entries have equal colours.

1.3.2.3 Convex relaxations

The current industrial approach to clearance of flight control laws consists in gridding the parametric domain and checking a set of criteria at each point of the grid. The main drawback of this strategy is that clearance is restricted only to the considered grid points and nothing can be assessed for the remaining points in the parametric domain. Moreover, significant time and money is frequently spent on this task.

The objective was to develop convex relaxations for non-convex optimization problems arising in robustness analysis of uncertain systems relevant to CFCL. Two clearance criteria have been considered: i) aeroelastic stability of integral models; ii) un-piloted stability of nonlinear models. These criteria have been tackled by applying robustness analysis techniques to the LFT models.

For the first clearance problem, several sufficient conditions based on Lyapunov theory have been considered and formulated in terms of LMI optimization problems. Moreover, an efficient method for performing μ-analysis has been proposed.

More precisely, a new mu-analysis based technique has been introduced to compute a guaranteed robustness margin for a high-order plant affected by numerous parametric uncertainties. It relies on the Matlab routine mussv.m, which is available with the Robust Control Toolbox and implements an efficient and fast numerical procedure to compute a mu upper bound at a single frequency point. The originality of the proposed approach is then to combine this local computation with a powerful frequency segments elimination technique in order to get a guaranteed mu upper bound over a large frequency range. Two efficient algorithms based on mu-analysis have been proposed to compute either a guaranteed robustness margin for a high-order linear time-invariant plant with numerous uncertainties or a guaranteed stability domain for a high-order parameter dependent plant. A whole Matlab package including detailed documentation has been released, which allows non-expert users to fully benefit from these theoretical results. It has also been shown how these tools can be more widely exploited to evaluate some of the clearance criteria that need to be assessed during the certification process of an aircraft, such as the eigenvalue and the stability margin criteria. Numerous tests have finally revealed that the proposed clearance methodology allows to handle high-order flexible plants that cannot be analyzed rigorously using classical methods. Indeed, conservatism is easily mastered and computational time remains quite reasonable, even if very demanding problems are considered. The modelling methodology and the aforementioned clearance tool are the two main stages towards the development of a modelling and optimization tool dedicated to the clearance of stability criteria, which is able to meet the industrial needs.

For the second problem, Lyapunov-based techniques have been employed to cope with mixed LTI-LTV uncertainties. Software tools and a graphical user interface for performing the considered clearance procedures have been provided. They have been employed by AIRBUS to compare the proposed techniques with the existing baseline solution. The considered clearance problems have been successfully solved, on a large set of LFT models representative of the longitudinal dynamics of a civil aircraft. The obtained results are promising because they foresee the possibility of introducing in the industrial clearance process optimization-based methods which permit to clear a full flight envelope and/or uncertainty domain, instead of only a finite set of nominal models.

Although further work is needed to reduce the computational burden (especially for Lyapunov-based methods) and to validate the LFT modelling process, it is believed that robustness analysis will become an integral part of the industrial clearance process in the next ten years.

1.3.2.4 Structure exploiting algorithms

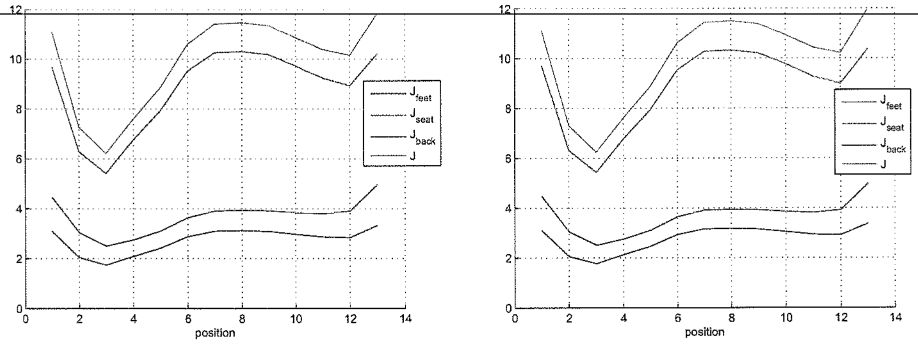
The main objective was to formulate the criteria considered into semidefinite programs and to investigate if it was possible to exploit the structure in these optimization problems to speed up computations and/or use less memory.

The considered criteria were formulated as semidefinite programs. For all criteria theory based on integral quadratic constraints (IQCs) was used. IQC analysis can simultaneously handle a wide variety of uncertainties, varying parameters and nonlinearities.

After thorough tests it was realized that already existing structure-exploiting algorithms were not applicable to the problems at hand. The difficulty to analyze complex models was handled by partitioning the parameter space. The partitioning yields many advantages:

- In many cases one can use simple IQCs to prove stability in a small partition.
- One can use model reduction to get less complex models. In a small partition simpler models can be used to describe the system.
- One can combine the above strategies to further reduce computational time.

It was possible to successfully clear a subset of the models developed in the project. For the nonlinear rigid aircraft model good results were shown when the eigenvalue criterion was addressed. However, there were some difficulties when the last stage in the analysis was performed. Also, the results when considering the comfort criterion for the integral aircraft were promising. The baseline solution applied to the linear fractional models developed in the project produced almost identical results to the proposed analysis method based on IQCs as can be seen in the figure below, where the baseline solution is shown to the left and the IQC based solution is shown to the right.



To really make the methods attractive to the industry future work has to be more focused on developing structure-exploiting methods for optimization problems of this specific type. Furthermore, more work should be done to improve numerical properties for these problems.

It is also important to realize for what problems not to use IQC analysis. Such a case is the eigenvalue criterion for the integral model. This problem fits perfectly into the class of problems which can be analysed using mu-analysis. IQC based analysis is more general than mu-analysis but the price to pay is a higher computational complexity.

1.3.2.5 Non-linear programming for parameterized pilot input

The objectives was to study and develop clearance methodologies for time-varying pilot inputs. Initially a literature study was done, which review relevant techniques, and also a study of the Airbus model was conducted. Later on, particularly, nonlinear programming for a parameterized pilot input signals has been studied. The basic idea is to find the combination of the pilot signal, flight condition and uncertainty resulting in the worst possible violation of protection systems (for example alpha protection). The algorithm and method development during the project have resulted in two software packages for search for a worst case manoeuvre. In the first package, called COFOPT, the stochastic global methods Genetic Algorithms and Differential Evolution have been implemented as well as the deterministic global method DIRECT. Also a local method, Pattern search has been implemented. For the other package, built on a quasi-Newton method, efforts have been made to achieve fast convergence and confirm local minima. Among the functionality included are the use of a second search direction, if the first one fails, and to use a cyclic optimisation method, as a terminal method after the quasi-Newton method. Also the structure of the optimisation problem, such as causality, has been utilized in order to reduce computational time. Efforts have been done to make the two packages general and easy to adapt. For both packages, the possibility to use parallel computing in order to compute the value of the objective function in parallel has been added. The cost of computing the objective function totally dominate the computations; the evaluation of the objective function is based on simulating the Airbus model (in a Matlab/Simulink environment). Both packages have been demonstrated effective in finding worst case violations based on parameterized pilot signals.

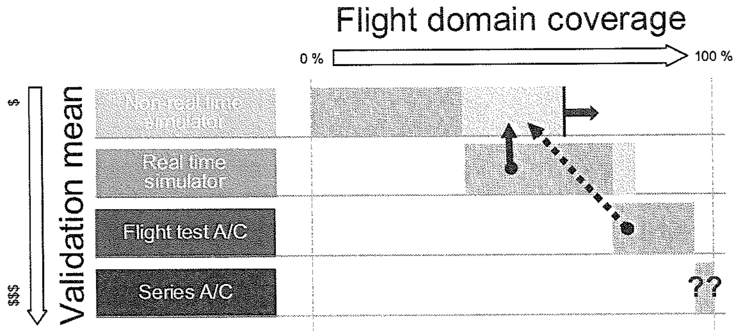
1.3.3 Evaluation

In the evaluation work package, the link between research techniques and industrial processes has been assessed. The idea has been to evaluate each clearance technique developed on a challenging industrial benchmark representative for a flight control clearance problem. Then the results given by each technique and the adequacy level of each technique to an industrial clearance has been assessed.

1.3.3.1 Benchmark

The first activity was about formulating a realistic clearance benchmark problem. Two benchmarks were finally submitted. The first benchmark comprises clearance of flight control law considering both rigid aircraft and non-linear modelling of the closed loop. Two major issues have driven this choice: performance assessment in a nonlinear framework, and validation of requirements on the whole flight domain considering a wide class of pilot inputs and wind perturbations. The second submitted benchmark was about flight control law clearance on flexible aircraft. Because of a better overall aircraft design optimization and widening of aircraft sizes, bandwidth of bending modes slow down and comes very close to the rigid body mode. Then two major issues arise: control laws must not over-shoot loads objectives assigned by structural aircraft design, and control laws can help designers in optimizing the a/c structure by reducing the limit loads.

The second activity was the description of the baseline solution in order to be able to evaluate the enhancement after partners had developed their own clearance methodologies. The validation is today performed using a wide set of means from batch simulation to flight tests. The main objective for AIRBUS (see the following figure) is to be able to detect bad behaviours as soon as possible in the validation process so as to be able to quickly (and then for a low price) modify the design. Current practices are mainly based on gridding and Monte Carlo based approaches. The main expectation is thus to get either faster worst-case detection methods or a continuously cleared region (rather than a finite set of points).



1.3.3.2 Evaluation of new techniques against baseline solution

An evaluation of the new techniques developed was conducted on the basis of the benchmark. At first, evaluation was performed separately but in a unified framework to obtain the global picture. Thus a common part of the benchmark was selected to be tested on all the methods. The evaluations were performed at the AIRBUS facilities. The easiness to implement the methods for a non-expert user was assessed, especially how the tuning parameter values should be chosen. Compromises related to the different methods were pinpointed. The efficiency, relevance, and usefulness of the methods were investigated by comparing results to the ones obtained from the baseline solution. Once each method had been individually investigated, a comparison was made between the different methods, and a more thorough investigation of the most promising method was performed. The set of methods has, as previously have been explained, been split in two sets, one containing sufficient methods and one containing necessary methods. Here are the main outcomes for these two sets:

- Sufficient methods should be used in the first design validation loop to perform the linear tests (stability analysis, robustness margins for uncertainties, ...). The analysis methods computational burden seams to be no more an issue and the result in itself is really more powerful than today's baseline gridding based solution. But we need an efficient modelling process which is maybe missing today (it was not necessarily one of the project identified objective ...). The aircraft LFT model generation process should be integrated in the reference modelling tool as it is the case today for the point-to-point linearization to be automatic from the control law designer point of view. The symbolic way is attractive but it ends up with really high order LFT model (see AIRBUS/ONERA studies) because of aerodynamic nonlinearities and highly repeated varying parameters. Nevertheless it seams to be one of the easiest ways to handle the modelling error in the validation process without use of a gridding-based approach. Once an open loop A/C LFT model is generated, controller LFT should be generated directly using LFT design tools. It should be an integrated process; otherwise time investment is not valuable compared to the today gridding approach.

- Necessary methods provide a result which is quite different from the one that can be obtain with the gridding based approach. There is no more the idea of a domain; only worst-case value and arguments are provided. However, the provided methods are usually able (i.e. with an high probability) to find cases that are worse than those obtained using Monte-Carlo base approaches when the same amount of simulations are performed. Optimization is therefore no more a competitor but it could be used as a complement to the gridding or Monte-Carlo based approaches. From an industrial point of view, those methods are now really mature and were shown to be ready for a fast integration in the industrial process.

1.4 End results

The project has resulted in new modelling techniques as well as new optimization based clearance techniques. It has been demonstrated on an industrial benchmark that the new techniques are very promising, and it is the intention of AIRBUS to use the new techniques in their development process.

1.5 Intensions for use and impact

Industry has made a huge step forward thanks to the COFCLUO project and a part of the developed methods will be certainly used in a development context within AIRBUS. Later on when confidence has been gained internally, AIRBUS could propose to airworthiness authorities that they include the methods in the official clearance process. Some of the results of the project will be developed into production quality clearance tools. These tools will either be sold or licensed, and used in-house or for consulting services. The results from the project are useful not only for clearance of flight control laws for civil aircraft but also for military aircraft. Many of the results obtained are general and can be adapted for clearance of control laws for vehicles other than aeroplanes, such as unmanned aerial vehicles, cars and trucks. Flight clearance for unmanned aerial vehicles is expected to be even more important than for manned aircraft. For the car industry, one application of optimisation-based clearance of control laws could be to improve the reliability of existing systems, such as vehicle stability control and traction control. Another application in future control systems development is automatic obstacle avoidance. The results obtained can also be used in the connection of validation of many other different types of systems, and thus the results will strengthen the ability of European industry to validate safety-critical systems in general.

1.6 Partners involved

Linköpings universitet, Sweden, Airbus France SAS, France, Deutsches Zentrum für Luft- und Raumfahrt e.V., Germany, Office National d'Etudes et de Recherches Aérospatiales, France, Swedish Defence Research Agency, Sweden, Universita' degli Studi di Siena, Italy

1.7 Co-ordinator contact details

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2 Dissemination and use

All public deliverables of the project can be downloaded from

http://er-projects.gf.liu.se/~COFCLUO

Later on they will be moved to

http://www.control.isy.liu.se/~hansson/COFCLUO

Two workshops on clearance of flight control laws were organized within the project. Their web-sites are located at

http://www.unisi.it/eventi/cofcluo/index.htm
http://www.control.isy.liu.se/~hansson/COFCLUOworkshop

2.1 Publications

The project has resulted in the following publications:

C. Roos
Generation of flexible aircraft LFT models for robustness analysis,
Proc. of 6th IFAC Symposium on Robust Control Design, Haifa (Israel), June 2009.

D. Petersson and J. Löfberg,
Optimization based LPV-approximation of multi-model systems,
Proc. of European Control Conference, Budapest, Hungary, August 2009.

D. Petersson and J. Löfberg,
Licentiate thesis, ISY, Linköpings universitet, 2009.

H. Pfifer and S. Hecker
Generation of optimal linear parametric models for LFT-based robust stability analysis and control design,
IEEE Transactions on Control Systems Technology, special issue on "Applied LPV modelling and identification" (to appear)

Ch. Papageorgiou, R. Falkeborn, A. Hansson,
Formulation of the Stability Margin Clearance Criterion as a Convex Optimization Problem,
Proc. of 6th IFAC Symposium on Robust Control Design, Haifa (Israel), June 2009.

H.-D. Joos, Flight Control Law Clearance Using Optimisation-Based Worst-Case Search,
Proc. of 6th IFAC Symposium on Robust Control Design, Haifa (Israel), June 2009.

D. Skoogh, P. Eliasson, F. Berefelt, R. Amiree, D. Tourde, L. Forssell, Clearance of Flight Contral Laws for Time Varying Pilot Input Signals,
Proc. of 6th IFAC Symposium on Robust Control Design, Haifa (Israel), June 2009.

A. Garulli, A. Masi, S. Paoletti, E. Turkoglu,
Clearance of flight control laws via parameter-dependent Lyapunov functions,
Proc. of 6th IFAC Symposium on Robust Control Design, Haifa (Israel), pp. 337-342, June 2009.

A. Garulli, A. Masi, A. Vicino
Convex relaxations for quadratic distance problems,
Proc. IEEE Conference on Decision and Control, Cancun (Mexico), pp. 5444-5449, December 2009.

A. Garulli, A. Masi and A. Vicino,
Relationships among different SOS-based relaxations for quadratic distance problems,
Proc. of the 6th IFAC Symposium on Robust Control Design, Haifa (Israel), pp. 66-71, June 2009.

Clément Roos and Jean-Marc Biannic,
Efficient computation of a guaranteed stability domain for a high-order parameter dependent plant,
To be presented at the American Control Conference, Baltimore, July 2010.

There will be 18 chapters of a book to be published by Springer Verlag: *Optimization Based Clearance of Flight Control Laws - A Civil Aircraft Application* (Eds. Andras Varga, Anders Hansson, Guilhem Puyou)

2.2 *Exploitation*

2.2.1 Trimming software for MATLAB

Result description

The developed software represents a powerful tool for trimming nonlinear aircraft models. This tool consists of a MATLAB based trim-function, `trimex.m`, which extends the functionality and capabilities of the standard trim-function `trim.m` of MATLAB. The underlying solvers are based on a nonlinear system solver and an alternative nonlinear least-squares solver. The latter allows defining bounds on the trimming variables. These solvers are implemented as mex-functions, and besides higher speed, they guarantee highly accurate trim computations. The primary purpose of this tool in the COFCLUO Project was to support the generation of LPV models by generating linear multi-models via repeated trimming and linearizations. Also this tool formed the basis of efficient evaluation of simulation-based clearance criteria, where the first computation consists of trimming the aircraft.

Possible market

The tool can be used by industries or research institutions, where the computation of equilibrium points is necessary. Main applications areas are nonlinear aircraft simulations, generation of linearized models, clearance criteria evaluation.

Stage of development

The software is a prototype that still needs some further development to become a fully user-friendly tool. A highly versatile GUI interface has been already developed to allow an user friendly definition and choice of trim conditions. This GUI can be further enhanced to support further trimming problems.

Collaboration sought or offered

No collaboration is needed to complete the software development.

Collaborator details

No specific partner is sought.

Intellectual property rights ***granted*** *or published*

The intellectual property rights will be protected via copyright. Access to the software will be subject to a license agreement.

Contact details

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Gertjan Jooye, DLR Oberpfaffenhofen (Germany), gertjan.looye@dlr.de

2.2.2 MATLAB software for LPV generation

Result description

During the project a general approach was developed to generate a linear parameter varying (LPV) state-space model, which approximates a nonlinear system with high accuracy and is optimally suited for LFT-based robust stability analysis and control design. At the beginning a Jacobian-based linearisation is applied to generate a set of linearised state-space systems describing the local behavior of the nonlinear plant at the corresponding equilibrium points. These models are then approximated using multivariable polynomial fitting techniques in combination with global optimisation. The objective is to find a linear parametric model, which allows the transformation into a Linear Fractional Representation (LFR) of least possible order. A gap metric constraint is included during the optimisation in order to guarantee a specified accuracy of the transfer function of the linear parametric model. The effectiveness of the LPV generation tools has been demonstrated by generating very accurate LPV models and LFRs for the COFCLUO nonlinear aircraft model. The LPV-generation toolbox consists of about 15 m-functions which produce LPV-models in symbolic representations. These models serve as inputs for the symbolic preprocessing tools developed by DLR for the LFR-Toolbox V2.0 (joint DLR/ONERA development), which produce LFT-models to be used in the Robust Control Toolbox of MATLAB.

Possible market

The software is a prototype that still needs some further development to extend its functionality towards LPV-model validation.

Stage of development

The tool can be used by industries or research institutions, where the development of LPV/LFT uncertainty models is necessary. Main applications areas are robust controller synthesis and solving clearance problems formulated as robustness analysis of uncertain systems.

Collaboration sought or offered

No collaboration is needed to complete the software development.

Collaborator details

No specific partner is sought.

Intellectual property rights granted or published

The intellectual property rights will be protected via copyright. Access to the software will be subject to a license agreement.

Contact details

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2.2.3 LPV and LFT-based uncertainty models for open and closed-loop aircraft

Result description

A collection of LFT-based uncertainty models has been generated for both open and closed-loop aircraft. The orders of the closed-loop LFT-models are around 300 and thus the LFT-models represent real challenges for presently available robustness analysis tools (e.g., in MATLAB). Furthermore, these models can serve as benchmark examples for further research on model reduction of multi-dimensional systems. The LFT-models are provided in a MATLAB compatible data format.

Possible market applications

The LFT models can be used by research institutions as benchmarks to develop new robustness analysis techniques able to handle large order LFT-models as well as for developing order reduction methods for LFT-models.

Stage of development

The models are given in MATLAB format. No further updating of models will be done.

Collaboration sought or offered

No further collaboration is needed.

Collaborator details

No specific partner is sought.

Intellectual property rights granted or published

The models are free to be used for research and development purposes.

Contact details

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Carsten Döll, ONERA (France), carsten.doll@onera.fr
Clement Roos, ONERA (France), mailto:clement.roos@onera.fr

2.2.4 LFT model generation techniques

Result description

The LFT model generation techniques proposed by ONERA have been implemented in a Matlab toolbox dedicated to the modeling of systems affected by structured uncertainties. Two types of LFT models have been generated. The first one consists of high accuracy, consistent and low order LFT models covering a set of linearized high order flexible aircraft models. The second one consists of high accuracy, low order LFT models for the nonlinear controller based on a block diagram structure for both the rigid nonlinear and the flexible linear aircraft models. Both techniques can also be used in a more general framework to assess the robust stability and performance properties of a system affected by structured uncertainties.

Possible market applications

The toolbox can be used by industries or researcher institutions that have to treat problems, especially for clearance processes, which can be formulated as uncertain system modeling. Examples of applications include certification of rigid and especially flexible structures such as aircraft, missile, launchers, satellites, and analysis of parametric robustness of control schemes for industrial plants or manufacturing systems like rolling mills.

Stage of development

The new software is compatible with the already available Linear Fractional Representation-Toolbox and its block library for use with Simulink. It must however still be improved in terms of user-friendliness and must still be generalized. It will be updated during 2010 in an in-house project and included in the next release of this toolbox (release date end 2010).

Collaboration sought or offered

No collaboration is needed to add new software functions to the LFR-Toolbox, its block library for use with Simulink and its links to the Skew-Mu-Toolbox. Any information on the usage of all toolboxes will be provided upon request.

Collaborator details

No specific partner is sought.

Intellectual property rights granted or published

The intellectual property rights of all toolboxes, the LFR-Toolbox, its block library for use with Simulink and the Skew-Mu-Toolbox are protected via a copyright and a license agreement. They are distributed as freeware from the ONERA's website. The new functions will be available with a new release end of 2010.

Contact details

Jean-Marc BIANNIC, ONERA (France), jean-marc.biannic@onera.fr

2.2.5 A framework for identification of LPV uncertainty models

Result description

The developed framework includes methods and theory regarding the generation of LPV models. This framework will form the basis for the continued research for a PhD student at LiU.

Possible market applications

The outcome will be used as a starting point for further research in the field and as the basis for D. Petersson's Ph.D. work at LiU.

Stage of development

The framework can be considered a theoretical prototype to be further developed and enhanced. The software is a prototype intended to serve as software demonstrator.

Collaboration sought or offered

No further collaboration is needed.

Collaborator details

No specific partner is sought.

Intellectual property rights granted or published

There are no intellectual property rights issues with this exploitable result.

Contact details

Daniel Petersson, Linköpings universitet, (Sweden), petersson@isy.liu.se

2.2.6 Optimization-based robustness assessment tool

Result description

Within the COFCLUO project a software demonstrator was developed for optimization-based clearance of flight control laws and has been successfully applied to the industrial benchmark problem. In general, this tool provides an environment for robustness assessment of engineering applications. Assessment or clearance problems are translated to worst-case search problems solved by optimisation. This approach is characterized by generality, non-conservatism and reliability and thus can be applied to any model-based robustness assessment not only for clearance of flight control laws.

The software tool supports the generality of the approach by an open interface for parameters, models and criteria and is ready for industrial operation. It is based on DLR's optimisation tool MOPS. Computation is fully parallelized in order to improve computing time.

Possible market applications

The tool can directly be used in DLR research and DLR projects.
It can be utilized in industry for any computer aided design or assessment based on simulation and analysis models.

Stage of development

Demonstrator, research product.

Collaboration sought or offered

Collaboration sought for information exchange on optimization; collaboration offered for training and consultancy.

Collaborator details

Collaboration sought with universities; training and consultancy offered for users.

Intellectual property rights granted or published

Copyright; access to software subject to licence agreement with DLR.

Contact details

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2.2.7 Software tool for robustness analysis (UNISI)

Result description

Within WP2.3 of the COFCLUO project, a software demonstrator has been developed for tackling robustness analysis problems relevant to clearance of flight control laws.
This tool provides several methods to perform robustness analysis of models in linear fractional representation (LFR), based on Lyapunov techniques. The software consists of a set of Matlab routines and a graphical user interface that facilitates the selection of the options available for each clearance technique and the analysis of the obtained results.
The techniques implemented are fully general and can be easily applied to robustness analysis of LFR models, arising in a large variety of control applications.

Possible market applications

The tool can be used by industries or researcher institutions that have to perform clearance processes formulated as robustness analysis of uncertain systems. Examples of applications include certification of flexible structures, such as airplanes or wind turbines, and analysis of parametric robustness of control schemes for industrial plants or manufacturing systems.

Stage of development

The software is a prototype that still needs some further development to become a fully user-friendly tool. A procedure to generate and upload new uncertainty models in the correct format has to be developed. New features can be added, allowing to perform more accurate robustness analysis (e.g., accounting for the presence of slowly time-varying parameters).

Collaboration sought or offered

No collaboration is needed to complete the software development. Any information on the usage of the graphical user interface will be provided upon request.

Collaborator details

No specific partner is sought.

Intellectual property rights granted or published

The intellectual property rights will be protected via copyright. It is planned to distribute the software freely in late 2010.

Contact details

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2.2.8 Software tools for robustness analysis (ONERA)

Result description

Within the COFCLUO project, the mu-analysis based technique proposed by ONERA has been implemented in a Matlab toolbox dedicated to clearance of flight control laws. Two criteria can be evaluated: the eigenvalue criterion and the stability margins criterion. The proposed clearance methodology allows to handle high-order flexible models that cannot be analyzed rigorously using classical methods. It can also be used in a more general framework to assess the robust stability and performance properties of a system affected by structured uncertainties.

Possible market applications

The toolbox can be used by industries or researcher institutions that have to treat problems, especially to perform clearance processes, which can be formulated as a robustness analysis problem of uncertain systems. Examples of applications include certification of rigid and especially flexible structures such as aircraft, missile, launchers, satellites, and analysis of parametric robustness of control schemes for industrial plants or manufacturing systems like rolling mills.

Stage of development

The new software is a user-friendly function which is fully compatible with the already available Skew-Mu-Toolbox. It will be included in the next release of this toolbox (release date 2010).

Collaboration sought or offered

No collaboration is needed to add new software functions to the Skew-Mu-Toolbox and its links to the LFR-Toolbox. Any information on the usage of both toolboxes will be provided upon request.

Collaborator details

No specific partner is sought.

Intellectual property rights granted or published

The intellectual property rights of both toolboxes, the Skew-Mu-Toolbox and the LFR-Toolbox are protected via a copyright and a license agreement. They are distributed as freeware from the ONERA's website. The new function will be available with the new release during 2010.

Contact details

Jean-Marc BIANNIC, ONERA (France), jean-marc.biannic@onera.fr

2.2.9 4. Software tool for robustness analysis (LIU)

Result description

Within WP2.4 of the COFCLUO project a software package for robustness analysis relevant to clearance of flight control laws has been developed. This software package is based on the theory of integral quadratic constraints and provides methods to perform robustness analysis of linear fractional representation models. The software consists of a set of Matlab routines. The techniques implemented can be easily applied to robustness analysis of LFR models, arising in a large variety of control applications.

Possible market applications

The tool can be useful for anyone that have to perform robustness analysis of uncertain systems. Applications include analysis of rigid body and flexible structures.

Stage of development

The software is a prototype. It needs further development to become an industrial tool. However, the methods can be extended to incorporate time-varying parameters and uncertain dynamics to allow for a more general analysis.

Collaboration sought or offered

No collaboration is needed to further develop the software. If anyone would like to know how to use the software we will be happy to give the required information.

Collaborator details

No specific partner is sought.

Intellectual property rights granted or published

The intellectual property rights will be protected via copyright.

Contact details

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2.2.10 Software for worst case manoeuvre

Result description

The algorithm and method development in WP2.5 during the project have resulted in two Matlab software packages for search for a worst case manoeuvre. The worst case manoeuvre problem is set up as an nonlinear programming problem and solved by applying appropriate optimisation methods. In the first package, called COFOPT, stochastic global methods as well as the deterministic global method DIRECT.has been implemented. Also a local method, Pattern search has been implemented. For the other package, built on quasi-Newton method, efforts have been made to achieve fast convergence and confirm local minima on noisy objective functions. Also a cyclic optimisation method has been implemented intended as a terminal method to be used after the quasi-Newton method. The structure of the optimisation problem such as causality have been utilized in order to reduce computation time. Both packages have the possibility to use parallel computing in order to compute the objective function in parallel for different data.. Much of the software and methods for the two packages are general and can be adapted for other problems.

Possible market applications

The software may be used in the aerospace industry and research establishment for development and possible future certifications. Much of the developed methods and software are general and may be adapted for other sectors such as space and car industry.

Stage of development

Software demonstrator

Collaboration sought or offered

FOI seek collaboration with other research establishment and industry and offers to be a partner in research projects and also offers consulting service.

Collaborator details

FOI seek a partner in aerospace industry and research establishment to carry out joint projects or perform consulting service.

Intellectual property rights granted or published

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