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New Analysis Techniques for Clearance of Flight Control Laws

An overview of GARTEUR Flight Mechanics Action Group 11

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Summary

Between April 1999 and September 2002, GARTEUR Flight Mechanics Action Group 11 FM(AG11) conducted research on 'New Analysis Techniques for the Clearance of Flight Control Laws'. To disseminate the results, a book was written and a special session on control law clearance has been organised for the AIAA Guidance Navigation and Control conference, August 2003. This report is based on a paper that served as an introduction for the other presentations in the special session. It explains the importance of the clearance task and it describes the application of five new analysis techniques to a benchmark clearance problem, with the objective of improving the efficiency of the clearance process. The techniques considered were μ-analysis, ν-gap analysis, a polynomial-based clearance method, a bifurcation and continuation method and an optimisation-based clearance. The main results, an industrial view and the conclusions and recommendations of the group are given.

Contents

(20 pages in total)

1 Introduction

Aircraft manufacturers have reached a high level of expertise and experience in flight control laws design. The current design and analysis techniques applied in industry enable flight control engineers to address virtually any realistic design challenge. However, the development of flight control laws from concept to validation is a very complex, multi-disciplinary task and the many problems that have to be solved make it a costly and lengthy process. Researchers from universities and research institutes have developed new, advanced mathematical methods for design and analysis that have the potential to improve the flight control law development process. In the past decade, the Group for Aeronautical Research and Technology in Europe (GARTEUR) has established action groups to investigate the potential benefits and drawbacks of several of these new synthesis and analysis methods.

From 1994 until 1997, the GARTEUR Flight Mechanics Action Group 08, FM(AG08), performed successful research on ‘Robust Flight Control’. A design challenge was carried out, in which robust control design methods were applied to both civil and military aircraft models. The results produced by this group are widely appreciated by the aerospace control community [1].

In 1999, the Flight Mechanics Action Group 11 was established to address a new and complementary challenge, focusing on the clearance process of the flight control laws. To disseminate the results, a book was published [2] and a special session on control law clearance has been organised at the AIAA Guidance, Navigation and Control conference in August 2003. This paper provides an introduction for the session. The material presented is largely based on [2], which comprehensively describes the work of the project.

2 Motivation for the Research

Many of today's high performance aircraft rely on an electronic flight control system (FCS) in order to provide acceptable piloting characteristics. This is especially true for fighter aircraft, which are often designed to be naturally unstable to improve performance. Multiple-lane, electronic flight control systems with sophisticated control algorithms, running on digital computers, are designed to assure integrity and reliability, and to provide the required stability, performance and handling characteristics.

The design process for modern FCS is a complex, multi-disciplinary activity, which has to be transparent, correct and well documented, in order to allow certification of the aircraft. The design and validation of the flight control laws (FCLs) is an important part of the FCS design and certification, as the safety of aircraft operations is primarily dependent on them. The FCL development process has a highly iterative nature of design and analysis activities. Basically, five phases can be identified:

1. **Off-line phase**, using desktop design, analysis and simulation,
2. **Pilot-in-the-loop tests**, using manned, real-time simulation,
3. **Iron-bird tests**, with hardware in the loop,
4. Formal **Clearance** of the control laws,
5. **Flight tests**.

This paper focuses on the formal clearance in the fourth phase where prior to flight tests, it must be proven to the clearance authorities that the flight controller is functioning correctly. Exhaustive analysis results from phases 1 until 3 are used to demonstrate that all certification criteria are fulfilled. As the costs of analysis runs increase exponentially each phase. Improved identification of the weak spots of the controller and worst case parameter combinations in phase 1, can lead to less required analysis in phases 2 and 3, thereby reducing the overall costs of the clearance process. Also, the chance of missing worst cases can be reduced by more effective analysis in phase 1.

Typically, for the purpose of clearance, criteria are employed that cover both linear and nonlinear stability, as well as various handling and performance requirements. For each point of the flight envelope, for all possible configurations and for all combinations of parameter variations and uncertainties[1], all violations of clearance criteria and the worst-case result for each criterion, have to be found. Based on these clearance results, flight restrictions may be necessary.

The number of cases that have to be checked is huge, especially for fighter aircraft. Many different store configurations have to be investigated, involving large variations of mass, moments of inertia and centre of gravity location. It must also be proven that the controller can cope with error tolerances on air data signals that are used for control law scheduling. The aerodynamic data that is used in the mathematical models for design and analysis can only be determined within given bounds. These uncertainty bounds have to be taken into account in the clearance. The models usually use linear approximations for nonlinear effects that are not fully known, or for nonlinearities that would make the model unacceptably complex. Since flying the aircraft in the presence of failures might involve the use of alternative control laws (e.g., by

[1] *Parameter variations* are usually well defined (e.g. aircraft mass variation during a mission). *Parameter uncertainties* are relatively small and are related to modelling inaccuracy.

switching to a backup control law after the loss of a certain sensor or a control surface failure), the additional cases that have to be investigated can be significant.

The huge amount of assessment work, typically on systems of very high order, requires fast, efficient and numerically reliable methods and routines for the calculation and visualisation of results. A major efficiency improvement can be expected by increased automation of the tools used for model-based analysis of aircraft behaviour. The objective should not be the faster production of analysis data, because a high degree of automation already exists. New techniques are needed for the faster detection of combinations of parameter values and manoeuvre cases for which flight clearance restrictions are necessary. Such ‘worst cases’ may be caused by rather obscure combinations of events and flight conditions, which makes it particularly difficult to detect them.

Over the past two decades, several mathematical techniques have been developed for the analysis of linear and nonlinear systems with uncertain parameters. Each of these techniques has its known strengths and weaknesses. However, at this moment it is still difficult for the aeronautical industry to assess whether their application would improve the efficiency of the FCL clearance process. The main objective of the research conducted by GARTEUR FM(AG11) was thus to explore the potential benefits of using advanced analysis methods for the clearance of flight control laws, by demonstrating some of the most promising techniques on realistic flight clearance problems.

It is important to keep in mind that the question addressed here is not a purely technical one, since industry is already technically capable of successfully clearing flight control laws. The main industrial benefits of 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 for a reasonable amount of effort.

3 GARTEUR Flight Mechanics Action Group 11

In 1999, GARTEUR FM(AG11) ‘New Analysis Techniques for clearance of flight control laws’ was established to address the research objectives described above. In this group, six European research establishments, seven industrial organisations and six universities participated. The project had five core activities, and a side activity for dissemination of results.

1. **Industrial clearance process.** The process and typical activities of the current industrial clearance task were described and potential areas of improvement were indicated.

2. **Models.** Three nonlinear fighter aircraft models were developed and modified for the purpose of the research. The HIRMplus is based on the generic fighter model HIRM (High Incidence Research Model), previously used by FM(AG08). ADMIRE (Aero Data Model In Research Environment) is a delta-canard configuration fighter model based on a realistic aerodynamic database, including the transonic region. The third model used is the Harrier Wide Envelope Model, based on a well-known V/STOL aircraft. The models were extended with flight control laws, and representative uncertainty ranges for the model parameters were defined to form clearance problems against which the methods could be assessed.
3. **Analysis Techniques.** Analysis teams from research establishments and universities applied five modern techniques which are new to the clearance process:
   - μ-analysis,
   - ν-gap analysis,
   - polynomial-based clearance,
   - a bifurcation and continuation method,
   - optimisation-based clearance.

   The classical industrial method was also used to provide a baseline solution.
4. **Visualisation Tools.** Analysis of a complex system produces complex results. Good visualisation is essential to gain a deeper understanding of the clearance results, upon which, important decisions about the airworthiness of an aircraft are based. By using a ‘wish list’ from industry, specifications were identified for visualisation tools that should assist in the clearance process by providing effective presentation of results for engineers and authorities.
5. **Industrial Evaluation.** The results of the analysis teams were assessed and evaluated by the industrial partners. The strengths and weaknesses of each technique were identified.
6. **Dissemination.** At the end of the project, the main results were captured in a book [2] and were presented at a final GARTEUR workshop.

The main results of these activities are presented in this paper.

4 Tasks and Needs of the Industrial Clearance Process

Before the analysis teams in FM(AG11) started applying their methods, they were given the relevant background information on the current industrial clearance process and areas where improvement is considered to be desirable and possible. Therefore, the industrial partners of FM(AG11) described the tasks and needs of this process. Several major steps in this process can be identified, which are summarised below.

Firstly, for a model-based clearance analysis, it is obviously important that a good, full-size nonlinear model of the aircraft and its controller is available, which includes all parameter uncertainties. From this nonlinear model, separate longitudinal and lateral linear (small perturbation) models can be generated. The engineers then familiarise themselves with the open-loop behaviour of the aircraft by computing stability plots and calculating the open-loop eigenvalues. Sensitivity studies on the effect of all individual parameter uncertainties on the aircraft stability can be performed, in order to obtain an understanding of which uncertainty parameters are the most relevant for the clearance.

After the engineers are well acquainted with the physics and dynamical behaviour of the aircraft and its controller, the main clearance task starts. The key question of the clearance, which any old or new analysis technique has to answer, is "*In which region of the flight envelope is the aircraft safe to fly?*" with its defined control system and assumed uncertainty ranges for its model parameters.

As used above, *safe* means to have a sufficient margin from instability. Just to prove stability of the augmented aircraft is not enough. For each point in the flight envelope (Mach, altitude and angle-of-attack), any stability margin violations must be found, as well as the worst-case stability margin and its associated uncertainty combination. Linear stability margin criteria, using an exclusion zone on Nichols diagrams are used for this purpose.

In addition to the stability requirements for the FCS, the aircraft should also possess good handling qualities. Various linear handling criteria are in use [3] [4], based on frequency domain and time domain calculations. The linear analysis is complemented by nonlinear simulations, which are used to check any problem areas discovered from the linear analysis. Nonlinear simulation is also used to investigate the effects of nonlinearities, to finally prove that the aircraft is fit for purpose or to derive limitations. Assessments are made to determine if rate and position saturation, limit cycles and exceedences of load factor or angle-of-attack limits occur. If such events do occur, it is important to know their duration, for which parameter combinations and its effect on the controllability of the aircraft. Both non-real-time nonlinear simulations and pilot-in-the-loop simulations are used.

All analysis results are documented in a clearance report and non-compliances of clearance criteria have to be addressed. In order to avoid flight envelope restrictions it is necessary to investigate whether reduced stability margins are acceptable or if improvements are possible by controller modifications.

5 The HIRM+ Benchmark Challenge

Three benchmark problems were developed, based on three different aircraft models. The models were augmented with control laws and a representative set of clearance criteria was defined for the analysis. In this paper, only the HIRM+RIDE benchmark will be discussed, as this model has the most complete set of analysis results available. More information on the publicly available ADMIRE model can be found on the Internet at http://www.foi.se/admire. The HWEM model is currently not publicly available.

5.1 HIRM+RIDE benchmark

The HIRM+ aircraft model is based on the High Incidence Research Model, originally developed by the former Defence and Evaluation Research Agency (DERA). The model is a generic fighter aircraft model with a canard, wing and tail configuration, as shown in Figure 1 in an artist impression. The aerodynamic data was obtained from wind tunnel tests and flight tests with an unpowered, scaled drop model. The model was set up to investigate flight at high angle-of-attack and high angles of sideslip.

Figure 1: The HIRM+ Aircraft

The original HIRM model was adapted to meet the needs of FM(AG11) by extending its flight envelope and adding parameter uncertainty ranges. The model is stable over most of the flight envelope, except for some combinations of angle-of-attack and control surface deflections. It does not include compressibility effects at flight in the high subsonic region.

The HIRM+ model was augmented with a Robust Inverse Dynamic Estimation (RIDE) controller, developed for the original HIRM model. The control laws are scheduled with dynamic pressure to provide consistent handling qualities over the extended flight envelope of HIRM+.

5.2 Analysis criteria

The criteria used in the current industrial clearance process can be divided into four classes:

I. linear stability criteria
II. aircraft handling/PIO criteria
III. nonlinear stability criteria
IV. nonlinear response criteria.

A complete clearance using all industrial criteria was not feasible during the research activity due to the limited time and resources available to the analysis teams. Therefore, it was decided to use a small, representative set of criteria and to analyse only a limited number of flight conditions. The following four criteria were selected:

1. Stability margin criterion (class I)
2. Unstable eigenvalue criterion (class I)
3. Average phase rate and absolute amplitude criterion (class II)
4. Angle-of-attack/normal load factor exceedence criterion (class IV).

Although originally intended, a nonlinear stability criterion was not considered because basic problems encountered in the application of the chosen criterion to the benchmark models would have taken too much time to solve.

5.2.1 Stability margin criterion

This criterion is used to ensure that the aircraft maintains adequate stability margins. The analysis of the stability margin criterion requires the identification of all violations of defined stability margin boundaries on a Nichols diagram, as indicated by the thick boundary in Figure 2. Furthermore, for each flight condition, the parameter uncertainty combination must be found which leads to the biggest violation, i.e. the worst-case parameter combination. Although only the violations are relevant for clearance, for analysis purposes the worst case is always of interest, even if the boundaries are not violated. This knowledge can be of use for future FCL development or modifications of the aircraft.

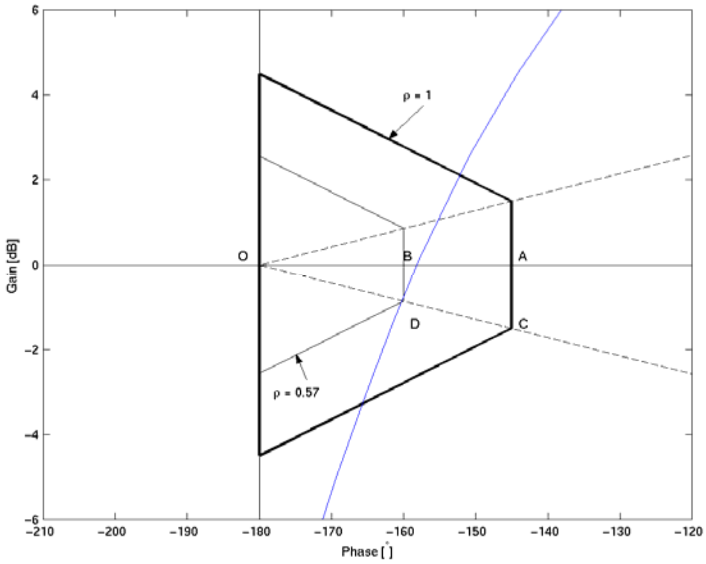

Figure 2: Nichols plot exclusion zone and the stability degree ρ

To find the worst case, the so-called 'stability degree' ρ was introduced, as indicated in Figure 2. The stability degree is 1 if the frequency response locus just touches the exclusion region. The stability degree is higher than 1 if the locus does not cross the exclusion region (criterion passed), and smaller than 1 if it crosses the exclusion region (criterion failed).

It should be noted that the exclusion region boundaries are not sacrosanct. They are not derived from theoretical calculations but are based on practical experience. Therefore, small violations of the boundary do not necessarily have to lead to flight restrictions if further investigations show that this is not required.

A single-loop analysis, in which each actuator loop is broken one at a time, is performed to assess the sensitivity of the system to changes in the dynamics of each actuation system. A multi-loop test is carried out to investigate the sensitivity to simultaneous changes in the dynamics of the actuation systems. These can, for example, occur due to a reduction in hydraulic pressure.

5.2.2 Unstable eigenvalue criterion

This criterion is used to assess the most severe cases of divergent modes (i.e. unstable eigenvalues), and the parameter combinations for which they occur. For each eigenvalue, the worst case is thus defined as the parameter combination that leads to the largest positive value of the real part. Not all eigenvalues in the right-half plane are considered as failing the criterion.

Unstable motion with a long time constant is allowed, as long as the eigenvalues remain on the left side of the region indicated in Figure 3.

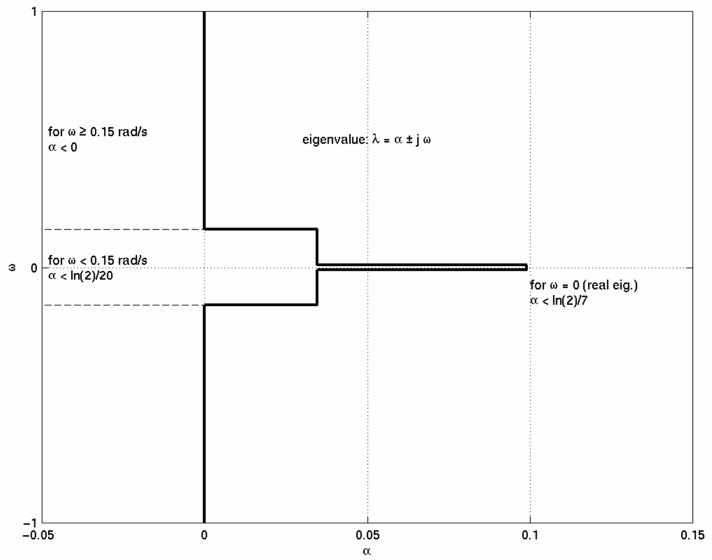

Figure 3: The Unstable Eigenvalue Region

5.2.3 Average phase rate and absolute amplitude criterion

These criteria are related to pilot-in-the-loop oscillations (PIO) and assess the stability of the pitch and roll attitude control loops which the pilot closes when flying the aircraft. The absolute amplitude test is to check that the system is not sensitive to 'pilot gain' and will provide satisfactory handling for a wide range of pilots. The average phase rate test is aimed at ensuring satisfactory dynamic response characteristics. The average phase rate and absolute amplitude are illustrated in Figure 4. The following two requirements had to be satisfied for HIRM+:

1. The average phase rate values of the frequency response of pitch/bank attitude to stick force should demonstrate at least Level 2 handling and therefore, not lie outside the Level 2 boundaries of the phase rate criterion shown in Figure 5.

2. For the pitch axis, add the following requirement as the second part of the criterion: the absolute amplitude of the frequency response of pitch attitude to stick force at -180 degrees should be less than -16dB [deg/lb] (equivalent to -29dB [deg/N]).

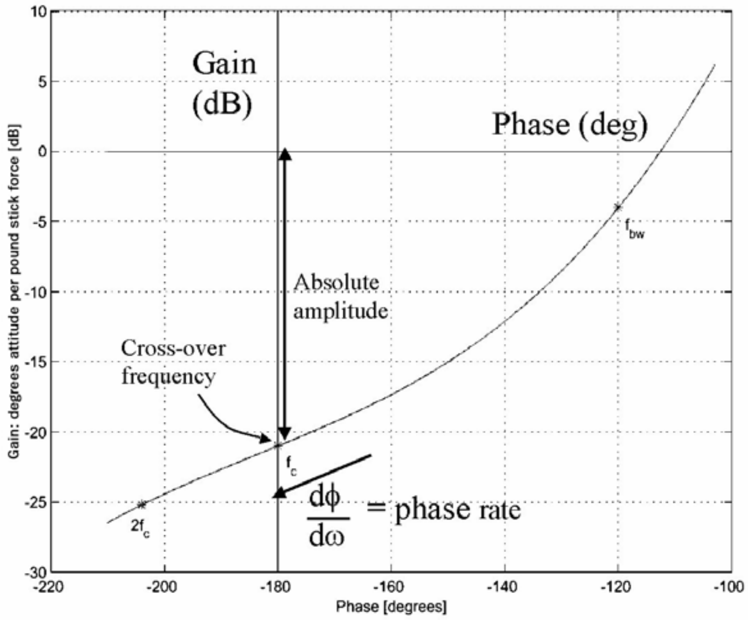

Figure 4: Absolute Amplitude and Average Phase Rate

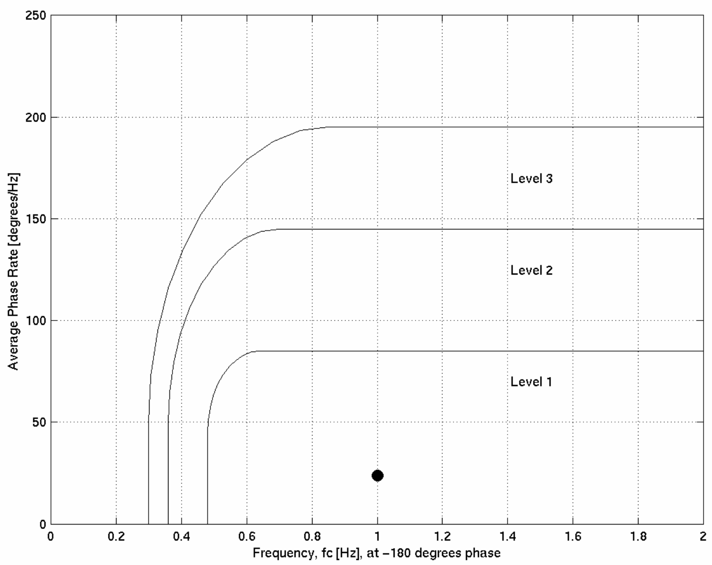

Figure 5: Average phase rate criterion diagram

5.2.4 Angle-of-attack/normal load factor exceedence criterion

This test is aimed at assessing the effectiveness of the incidence-limiting and g-limiting capabilities of the flight control system, in terms of the attained maximum values. For this test it is required to identify all flight cases where, for the pull-up manoeuvres defined below, the positive angle-of-attack and normal load factor limits (for HIRM+, 29° from its incidence limiter and 7g) are exceeded. This must be done for the nominal case and for the parameter tolerance case. The combination of uncertainties that yields the largest exceedence must be identified. Two pull-up manoeuvres were used for the HIRM+ analysis: a gradual, full-stick pull in three seconds, and a rapid full-stick pull with a stick rate of 1000 mm/sec (essentially a step command).

6 Application of Analysis Techniques

The research activity involved seven teams who applied five different new analysis techniques to the HIRM+ benchmark problem. In addition, a baseline solution, using the classical approach, was performed to serve as a reference for comparison. It should be noted that the list of analysis techniques applied in this research activity is not exhaustive. Other analysis techniques may exist which have great potential to improve the clearance process. The analysis teams were free to select their own preferred method.

6.1 The structured singular value and μ-analysis

This method uses the structured singular value μ, to form a test for robust stability of a closed-loop system, subject to uncertainties. In order to use μ-analysis, linear fractional transformation (LFT) based uncertainty models must be generated from the nonlinear model. As this is a key activity for this method, representing a large percentage of the effort, several approaches were investigated.

As the μ-analysis is, in principle, based on linear models, this method is most suitable for analysing linear criteria in the frequency domain, i.e. the stability margin criterion and the eigenvalue criterion. Worst cases (and the parameter combinations causing the worst cases) cannot be computed directly, but are approximated by calculating upper and lower bounds of μ. For clearance purposes, the upper bound can be taken to be on the safe side. This however, clearly introduces conservatism into the method. The method is potentially more reliable as it could be used to clear whole continuous regions of the parameter space, instead of only the vertices defined by the uncertainty ranges.

6.2 The ν-gap metric and the generalised stability margin

This method uses the generalised stability margin ε, which can guarantee stability of a closed-loop system and is used in H_∞ loop-shaping controller design methods. It introduces the ν-gap distance δ_ν, which can be viewed as a way to measure the importance of the difference in behaviour of two systems. The ν-gap can be used to measure the difference between a nominal system and a perturbed system (including uncertainties). The concept is illustrated in Figure 6.

As it is a linear frequency domain method, it is most suitable for analysis of criteria such as the stability margin criteria.

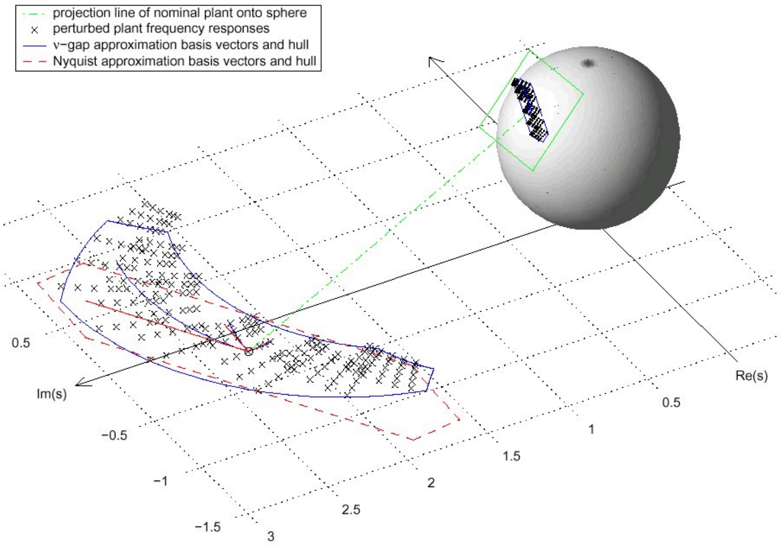

Figure 6 Mapping two systems P0 and P1 on to the Riemann Sphere, visualising the ν-gap

6.3 Polynomial-based analysis

This method checks the robust stability of a dynamic system by looking at the uncertain coefficients of the characteristic polynomial. The proposed method allows clearance if the eigenvalues of a system are located in a region D (robust D-stability problem). If, for the region D, the region in Figure 3 is taken, the eigenvalue criterion can be addressed directly. In fact, this method can address all stability criteria, which can be mapped to an eigenvalue problem. The method used an adaptive gridding approach to clear sections of the flight envelope which are as large as possible. The results were visualised in a very clear way over the flight envelope, as illustrated in Figure 7. The method is not suitable for nonlinear criteria.

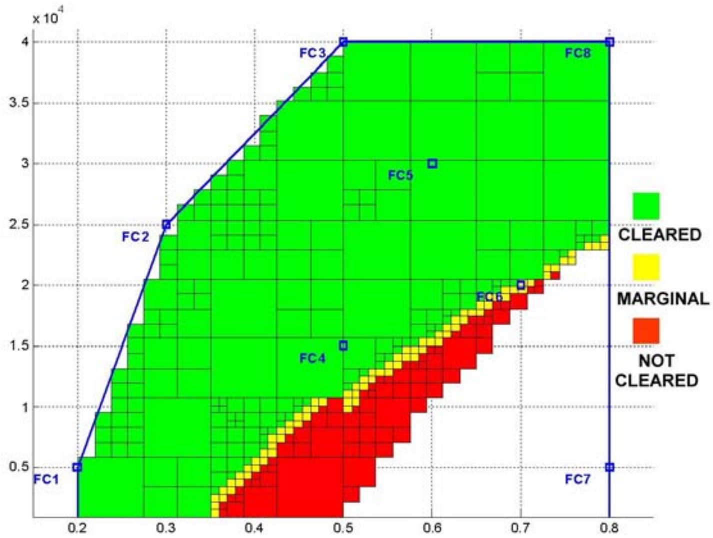

Figure 7: Visualisation of cleared and non-cleared regions in the flight envelope

6.4 The bifurcation and continuation method

Bifurcation theory can be used to analyse a system of nonlinear differential equations by assessing its steady and non-steady equilibrium solutions as a function of its state and input variables. This means that for the control law clearance problem of an aircraft model with uncertainties, the influence of any parameter can be analysed. It is implemented numerically by using a so-called continuation method. Bifurcation analysis is particularly powerful in relating the analysis results back to the underlying physics of the problem. It can yield the violations of the eigenvalue criterion directly, and provide useful insight into nonlinear phenomena and aircraft behaviour, when used in conjunction with nonlinear simulation. The method can be used for linear and nonlinear analysis.

6.5 Optimisation-based clearance

The concept of optimisation-based worst case search is to reformulate clearance criteria into a distance minimisation problem. By using an optimisation algorithm, the worst case can then be found as a function of uncertain model parameters. The main requirement is the availability of a parametric model describing the system’s dynamics. Various local and global optimisation routines are in use, and care should be taken to select the best method for the particular problem. The optimisation-based method is very flexible and can handle any linear or nonlinear criterion that can be represented by a mathematical expression.

7 Industrial View on the Performed Research

Each analysis team documented its process and results in a report that consisted of a tutorial part, in which the method was explained, and a part in which the analysis results were described. Based on these reports, the industrial members of the group assessed the strengths and weaknesses of each method, with the objective of determining if it has the potential to improve the efficiency (effort versus reliability) of the clearance process.

7.1 Evaluation procedure

Ten flight control specialists of the industrial partners evaluated the analysis reports by completing a questionnaire. Each method was assessed by at least three evaluators and in total, 21 individual evaluations were performed.

The evaluators rated each method on four main characteristics. The **generality** of the method indicates if the method can be used for a large number of criteria and problem types. Secondly, the **conservatism** of a method was evaluated. A method that is too conservative can lead to unnecessary flight restrictions or additional analysis effort. A method that is too optimistic can overlook problems with the control laws, which may then be discovered in flight. The **reliability** of the method relates to the capability of the method to correctly find all the worst cases and hidden weaknesses, throughout the flight envelope. Finally the **effort** of the method had to be rated. The effort could also be divided into four parts: learning the method, understanding the method, the computing time to produce the results and finally, the required man-time to apply the method and to interpret the results.

7.2 Evaluation of results: main conclusions

The main advantages of **μ-analysis** are the fact that parameter uncertainties can be directly taken into account, and that the method guarantees that whole regions of the parameter space can be cleared in one test. This implies that the method potentially provides better reliability than the current industrial gridding approach. The method introduces conservatism, as the worst case value needs to be approximated by calculating upper and lower bounds of μ. The main drawback is that the method cannot readily address nonlinear time domain criteria. In conclusion, it was found that μ-analysis is best suited as a last step of design or at an early stage of the clearance process. Reduced conservatism is essential if this method is to be used for the clearance of a FCS.

ν-gap presents a good way to find the relative effects of different parameters versus frequency. The method provides good insight into the effects of individual parameter variations on the aircraft’s behaviour. It can be thus used to find critical areas for further analysis. The main drawbacks are the fact that the method can only be applied to the stability margin criterion, and the theory of the method requires a high level of understanding of mathematics and algebra.

For the **polynomial-based method** it is claimed that potentially, any linear criterion can be analysed, although only the eigenvalue criterion was analysed. Nonlinear criteria cannot be addressed. The plots used to visualise results, although not specific to this method, are very illuminating. The computing time required is relatively high compared to the other methods. The polynomial-based method is considered to be appropriate for closer investigations of areas where the system is close to violating limits.

The main strength of **bifurcation analysis** is its straightforward link between the results and the underlying physics. Nonlinear criteria can be addressed, although this was not demonstrated. A weakness is that the method does not guarantee that the worst case has been found, but it will identify problem areas. Bifurcation could be used to enhance current methods by finding regions where closer investigation is needed. The method could be powerful if combined with the optimisation approach.

The most promising of the presented methods is the **optimisation-based worst-case search**, due to its generality. It can be applied to linear and nonlinear criteria in the frequency and time domains. A minor weakness is the selection of the optimisation algorithm. Global methods do not guarantee that the worst case will be found. Selection of computationally more efficient routines may sometimes compromise the reliability of the method, but overall, this flexible method increases the test coverage with reasonable computational effort.

7.3 Civil view

The research activity considered benchmark problems for military fighter aircraft. However, the civil and military clearance processes[2] have a lot in common. In verification and validation of flight control laws for large civil transport aircraft, the same tasks are performed and there is the same demand to confirm robustness of the design. Uncertainties in aircraft dynamics are of a similar nature for both, although the importance of certain areas and the range of potential variations vary. That is why the civil industry joined the industrial evaluation and qualitatively assessed whether the demonstrated analysis techniques have potential to improve their clearance process. Although spin-off for civil aircraft has thus been considered, it was decided at the start of the research effort to use only military benchmarks models. Modern fighter aircraft are usually open-loop instable, and they perform highly dynamical manoeuvres, including at high angle of attack conditions where the aerodynamical characteristics are highly nonlinear. Fighter

[2] For convenience, the term clearance is used, although this term is not common in the civil world, where this activity belongs to '*verification and validation*'.

aircraft thus pose a greater challenge for obtaining good results with analytical model-based techniques than for civil aircraft models that have more benign dynamics.

The details in which the civil and the military process differ are explained in [2] and [5] and shall be briefly summarised to better understand the particular civil demands for process improvements. Differences result mainly from mission requirements (passenger transport or military tasks), customer requirements (airlines or governments), and the specific civil and military certification regulations. This is reflected in variations in clearance criteria regarding stability, handling qualities, controllability, and manoeuvrability. The result is that in civil clearance, nonlinear analysis preponderates over linear analysis.

Consequently, those methods that can directly handle nonlinear criteria have the highest potential to improve the civil clearance process. Of the demonstrated methods, these are the optimisation- and bifurcation-based methods. From the other methods, the strengths of μ-analysis (including LFT) and the ν-gap method and several excellent ideas of the contributors could be favourably used in the design of control laws.

Finally, it was recommended to define an equivalent civil benchmark problem, to encourage research on analysis of nonlinear criteria, and to exploit the benefits of further advanced analysis techniques.

8 Conclusions

The main goal of the project was to explore the potential benefits of applying alternative mathematical analysis techniques to the industrial flight clearance process used for military aircraft, in terms of their flight control laws. In GARTEUR FM(AG11), five selected analysis techniques were demonstrated on the basis of the HIRM+ clearance problem and a representative set of analysis criteria. As a reference, a baseline solution was generated, using the current industrial methods for flight clearance. Each technique was applied to show its potential for improving the clearance process, with some interesting concepts and innovations being demonstrated. Finally, the strengths and weaknesses of the techniques have been qualitatively assessed by industry.
The research activity has been beneficial for all participants, and the GARTEUR platform provided an inspiring interchange of ideas and knowledge between industry and the scientific community. Universities and research institutes familiarised themselves with the practical problems of an industrial task. In return, the European aircraft manufacturers gained insight into the potential of state-of-the-art analysis techniques available in the scientific community. In this respect, it is considered that the objectives of this research activity were achieved.

It is important to note that the analysis techniques that have been applied are still undergoing development and therefore, improvements are to be expected. The knowledge and experience gained from this project will help the scientific world to tailor their analysis techniques, so that they are more specifically aimed at complex nonlinear problems such as the flight clearance task. Previously, only limited research in this area could be carried out, since the relevant information was not available in the public domain. The research effort of FM(AG11) should be viewed as a rigorous exploration of analysis techniques of different levels of maturity, instead of a final comparison between fully mature techniques. It is expected that there is more to come, as the methods are further developed.

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Universities:	Bordeaux, Bristol, Cambridge, Delft, Leicester, Stuttgart

More information is available on the web at:
http://www.nlr.nl/public/hosted-sites/garteur/rfc.html

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