AWIATOR'S DESIGN OF MULTI-OBJECTIVES CONTROL LAWS.

Matthieu Jeanneau*, Jérôme Lamolie[#]*, Guilhem Puyou*, Nicky Aversa*

** Airbus – Contact address: 316, route de Bayonne – 31300 Toulouse – France
Tel: +33 5 61 18 25 11 - Fax: +33 5 61 18 25 38 - Matthieu.Jeanneau@airbus.com
Ecole Centrale de Lille - BP 48 - 59 651 Villeneuve d'Ascq cedex - France*

Abstract: Following the works presented in St Petersburg during the 16th IFAC Symposium on Automatic Control in Aerospace, Airbus has been working on the design and evaluation of more integrated control laws, taking into account multi-objectives design criteria, gathering from the very beginning the specifications in term of handling qualities, comfort, loads, and robustness. A non-conservative H_∞ schema allows to directly associate each criterion to a dedicated exogenous transfer function and a tuning weighting. This approach offers an easy tuning, criterion by criterion, guaranteeing optimal results. This is also very convenient for industrial evaluation of reachable compromises between criteria, and Pareto-like plotting. *Copyright © 2005 IFAC*

Keywords: Multi-objectives control, Active control, H-infinity optimisation, Wing loads alleviation, Handling qualities, Comfort, Robustness, Flexible, Flight control, Control law reduction.

1. INTRODUCTION AND CONTEXT

This work has been conducted in the frame of AWIATOR. This European project involves more than 23 partners from Europe+Israel. Its target is the proof of concept and in-flight validation of wing (design) technologies for future aircraft application. Such technologies are illustrated in figure 1. They concern new devices such as large winglets, vortex generators, mini-TED, flap tabs, a LIDAR gust sensor, but also some new system functions allowing to compute and estimate wind in real-time, to generate calibrated wind using control surfaces, or to alleviate loads at wing root section.

The study presented in this paper deals with the design and flight test of flight control systems which provide weight saving and enhanced passenger protection in exceptional gusts through an alleviation of loads encountered at the inner wing. Past works conducted on this subject, see (Jeanneau, *et al*.), were focusing on actively controlling the structural oscillations of the wing. This dedicated function is introduced as an added feedback loop to the Flight Control Law (FCL). However, one of the load-function main constraint was not to interact with the handling qualities of the plane tuned by the FCL. This approach is conservative: firstly because it prevents from acting on the rigid mode yet responsible for about 50% of the wing loads, secondly because splitting the control into two separate loops with decoupling constraints is of course restrictive.
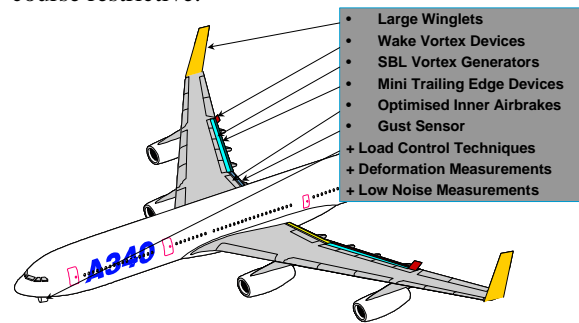

Fig. 1: AWIATOR technological features.

Today works investigate a more optimal approach, trying to gather into an integrated design usual FCL criteria along with load alleviation objectives. Section §2 describes the design criteria taken into account for multi-objectives control laws. Section §3 presents traditional design methods for comparison with the studied methods. Section §4 recalls the past R&T works that have inspired this study. Section §5 and §6 describes two different R&T approaches currently studied to enhance multi-objectives control law design methods. Questions about coding such control laws using Airbus certified automatic coding tools are raised in §7. Finally conclusions and prospects are addressed in §8. References of past works that have inspired this study are given in the final paragraph.

2. DESIGN OBJECTIVES

Below are listed main criteria to be taken into consideration when designing a flight control law for commercial aircraft. This list is restricted to criteria actually considered in the designs presented hereafter.

2.1 *Handling qualities (HQ)*

Stability

A minimum damping for the angle of attack mode (between 0.5 and 0.7) is searched.

Pilot orders

Longitudinal aircraft control is made through vertical load factor (*Nz*) orders. On a step side-stick input, the following requirements must be satisfied:
- Regarding vertical load factor *Nz* :
  o Time response similar to natural aircraft
  o Overshoot below a given value
- Regarding pitch rate *q* :
  o Initial rate ≠ 0
  o Overshoot below a given value

Wind

The aim is to cancel any static load factor shift induced by perturbations without oscillations. For this reason it is necessary to include integrators in the loop.
Handling qualities requirements are thus mainly time domain specifications. Pole placement methods are therefore well suited to take them into account.

2.2 *Loads in turbulence*

Loads correspond to internal structure efforts induced by turbulence and loads created by manoeuvres. Because loads in manoeuvres are closely linked with feedforward and kinematic design they are not considered in this study. Considering $H_i(s)$, the transfer function between the wind (spectrum *Φ*) and the ith effort, the turbulence load Y_i^{turb} is given by:

$$Y_i^{turb} = \sqrt{\frac{1}{\pi}\int_0^\infty |H_i(j\omega)|^2 \Phi(\omega)d\omega}$$

as illustrated in figure 2. Loads natural expression is thus the H$_2$ formulation. However it can be assumed that by reducing the peak of a resonance it induces a reduction of its area. Load reduction can be therefore be obtained using an H$_\infty$ criterion.
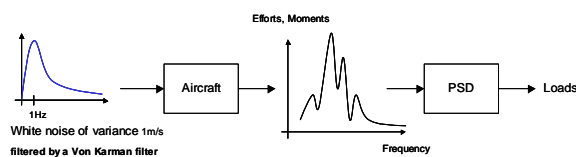

Fig. 2: Illustration of a load computation.

2.3 *Robustness*

Robustness is the controller design golden rule. Two levels of robustness are usually considered:
- Robustness in stability. The controlled system must remain stable considering uncertainties.
- Robustness in performance. The controlled system must keep an acceptable level of performance considering uncertainties.

Stability margins

In order to design a closed-loop which *remains stable considering uncertainties*, one usually try to reach given phase and gain margins on SISO loops. In a MIMO case, equivalent margins are obtained with the *T* and *S* sensitivity functions. A standard specification is then $\|T\|_\infty < 2$ and $\|S\|_\infty < 2$ in input as well as in output of the system (equivalent to 30° and 6dB of guaranteed SISO phase and gain margin).

Performances robustness

Uncertainties may come from some parameters influencing the aircraft dynamics. These parameters may either be time varying or uncertain. Some uncertainties also come from non-parameterised variations of aircraft.

- Structured uncertainties and variations:
  o Mass: from min to max
  o Balance: variations of centre of gravity
  o Inertia: linked to mass variations
  o Aerodynamic coefficients
  o Structural modes characteristics: frequency, damping.

Mass and balance variations, and aerodynamics uncertainties are tackled by worst-case choice in the design process. Concerning structural modes characteristics, it is quite easy to create an LFT model of the frequency and damping variations (Ferreres). Range of variation can therefore be expressed in H$_\infty$ constraints.

- Unstructured uncertainties. The main one is non-identified parts of the aircraft, i.e. the neglected dynamics whose influence on the design is minimised by using Roll-Off constraints.

The three robustness specifications (*T* and *S* margins, structural modes variation, roll-off) have thus an H$_\infty$ natural formulation.

2.4 *Control laws architecture*

To keep traditional flight control laws architectures, some actuators must not be used in certain frequency bandwidth. For example, traditional control makes use only of elevators to control pitch rate. However in an integrated multi-objectives design, it is necessary to use ailerons symmetric deflections to alleviate loads induced by wing oscillations. Some roll-on constraints are added to minimise the gains of the orders sent to ailerons at low frequency, then recovering a "traditional" control in the frequencies

of the rigid mode. Same kind of roll-on or roll-off constraints are applied to some of the measures available, in order to respect some conventional Airbus architectures, but also safety requirements (redundancy of critical sensors and actuators). All these roll-on and roll-off constraints have a natural H_∞ formulation.

3. TRADITIONNAL TUNING METHODS

When flight control laws were first introduced by Airbus on its fleet, main criterion was to offer a piloting by objectives, thus focusing mainly on rigid modes for performance, trying to minimise any interaction with structural modes.

3.1 *Pole placement with integrators*

Tuning of the laws traditionally consists in a state-feedback pole placement, including integrators in the feedback loops measuring the piloting objective: load factor in longitudinal, roll rate in lateral.

3.2 *Structural filtering*

When required by aircraft flexible characteristics, some low-pass filters are included in the feedback loops to prevent the law from exciting the structural modes.

3.3 *Remarks on this approach*

This approach has proven to be very reliable and effective. However it requires to check *a posteriori* that load constraints on the structure or robustness requirements are fulfilled, leading to an iterative design process between control laws design and *a posteriori* checks, either to fulfil the constraints, or to use the available margins to increase handling qualities performances. A multi-objectives design, taking into account all these requirements from the very beginning, would significantly improve the design and validation process, and the search for an optimal balanced solution between all constraints.

4. PAST R&T WORKS

Previous studies, published in (Jeanneau, *et al.*), were concerned about designing a load-dedicated control law in order to alleviate or control from the very beginning of the design process the level of loads on the structure, and thus avoid numerous *a posteriori* iterations. The approach retained was to include such a control law in addition to the current flight control laws. 2 control laws are therefore running in parallel, one dedicated to handling qualities, the other actively controlling structural oscillations for loads alleviation. This load function is itself divided into 3 parts as described by figure 3, each with a dedicated objective. First, a passive control reduces the loads induced by pilot inputs or by turbulence, by deflecting ailerons and spoilers proportionally to the vertical acceleration of the

aircraft. Secondly, an active control deals with wing oscillations induced by the bending structural modes. This part has been designed with modern H_∞ methods, to take into account and optimise various specifications: load reduction, robustness to payload, but also roll-on and roll-off criteria to avoid any interaction possibly modifying handling qualities. The third part concerns the activation logics of the first two parts.
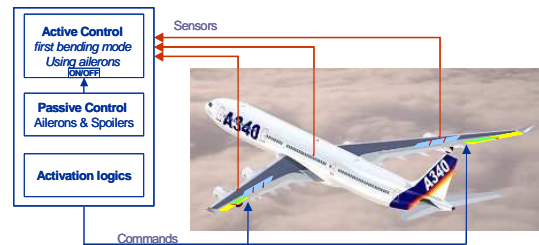

Fig. 3: Overview of a wing-load control law.

These R&T activities are now sufficiently mature to be currently used in Airbus aircraft design process when required.
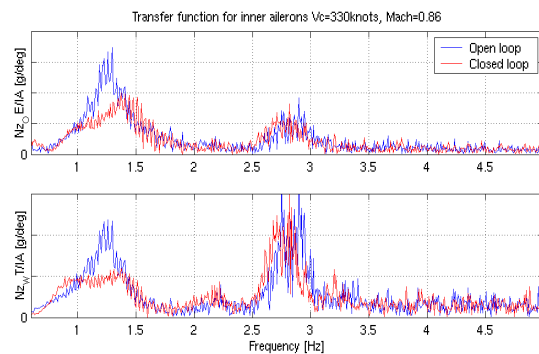

Fig. 4: Example of in-flight results obtained when the active control is active (in red) compared to aircraft response when inactive (in blue).

Figure 4 illustrates the performances obtained in flight with this approach. Frequency responses of the wing longitudinal accelerations with or without the load-dedicated law are plotted. These accelerations are measured at outer engines in the first subplot and at wing tip in the second. The wing bending mode (~1.2Hz) resonance is reduced by about 40%. Impact on handling qualities are negligible as required, which is visible below 0.5Hz for which open loop and closed loop plots are superposed. Same result is obtained on higher (>2Hz) structural modes which are unaffected by the law as required to prevent from any unexpected behaviour due to the difficult modelling of these modes. Finally stability margins were proven, as well as performance robustness to cruise flight points and mass cases.

5. MULTI-OBJECTIVES DESIGN USING MODAL TECHNIQUES AND H_∞

5.1 *Principle*

The approach described in this chapter is a 2 steps design first proposed by (Puyou, *et al.*). First step

consists of a pole placement of the rigid modes taking into account handling qualities criteria only. Second step consists in adding all other criteria: loads, robustness, roll-on and roll-off constraints, while trying to remain as close as possible to the law designed in the first step.

5.2 *Modal tuning*

This first step is based on modal techniques. Pole placement of the rigid modes is defined in the form of a rigid-states-only feedback: $U_{rig} = K_{rig} . X_{rig}$. This U_{rig} control law becomes, for the second step, the reference order for handling-qualities fulfilment.

5.3 *H_∞ design schema*

In this second step, all criteria are gathered into a dedicated H_∞ multi-objectives schema, as illustrated in figure 5. Final control law is expressed by:
$$U_\infty = K_\infty(s) . \text{ymeasures}.$$
The transposition into H_∞ of the following requirements is made through dedicated transfer functions:

o Recovering the handling-qualities reference law at low frequencies (with W_{LP} a low-pass filter):
$$\left\| W_{LP}.\left(U_\infty - U_{rig} \right) \right\|_\infty$$

o Damping the wing bending mode to alleviate loads (with W_{BP} a band-pass filter centred on the bending mode):
$$\left\| W_{BP}.\left(\frac{Nz_i}{wind} \right) \right\|_\infty$$

o Guaranteeing stability margins: $\left\| T \right\|_\infty$, with T the complementary sensitivity function.

o Robustifying the control to modes frequency variations δf: $\left\| \dfrac{Nz}{\delta f} \right\|_\infty$

o Preventing gains at high frequencies to avoid unexpected interactions due to difficult modelling of dynamics at high frequency: roll-off constraint:
$$\left\| G.(I + GK)^{-1} \right\|_\infty$$

o Avoiding gains on some actuators at low frequencies (roll-on constraint to recover classical architecture used for handling qualities control):
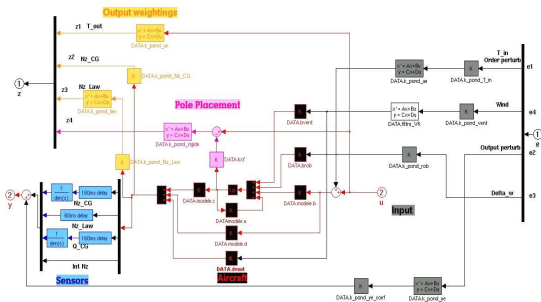$$\left\| W_{LP}.G.(I + GK)^{-1} \right\|_\infty .$$

Fig. 5: H_∞ schema for multi-objectives design method n°1.

5.4 *Method evaluation*

This 2 steps approach automatically optimises the interaction between:
- the rigid pole-placement,
- the active wing bending-mode damping,
and preserves the usual rigid pole-placement, which is the best way to express handling qualities criteria. Nevertheless it alleviates loads throughout the bending mode damping only, while loads at wing root comes ~50% from bending mode, and ~50% from rigid mode).

5.5 *Performances evaluation*

Figure 6 illustrates preliminary results obtained with this approach. One notices a very good damping of the wing bending mode (~1.2 Hz) while other constraints are also fulfilled (rigid mode placement, roll-off constraint above 2 Hz, roll-on constraint on
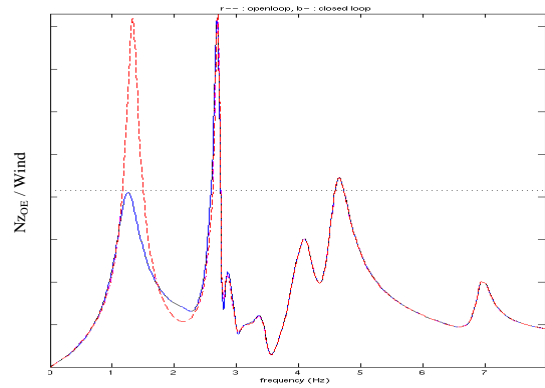
Fig. 6: Transfer function between wind and longitudinal acceleration at outer engines position: open-loop in red, closed-loop in blue.
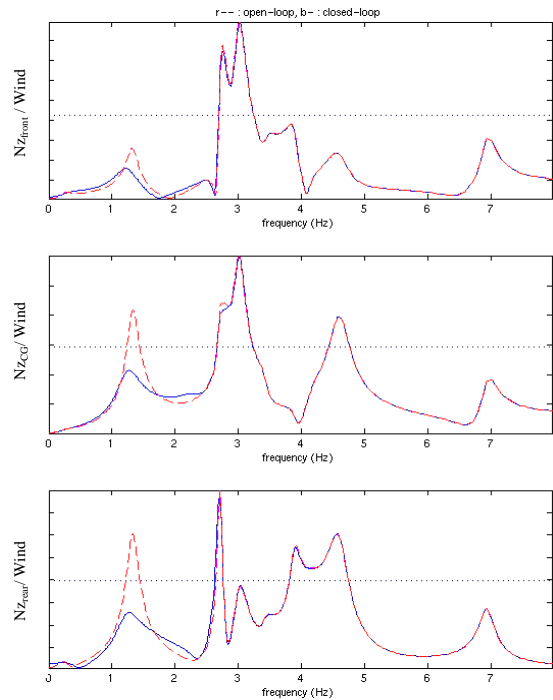
Fig. 7: Transfer functions between wind and longitudinal acceleration at different positions along the fuselage: open-loop in red, closed-loop in blue.

ailerons, stability margins, etc. Compare to results obtained with the past approach described in §4, the bending mode damping is even better. But more important, the interaction between handling qualities constraints on the rigid mode, and the damping of the first bending mode, is really optimised thanks to the integrated approach. This is noticeable when comparing figure 6 and figure 4. Both approach damp the bending mode, but lateral peaks can be noticed on figure 4. These undesired peaks come from the band-pass structure of the §4 approach necessary to prevent impacting handling qualities. On the opposite, the integrated approach illustrated by figure 6 automatically optimises these interactions.

Figure 7 shows how the wing bending dedicated law is also very efficient on the fuselage accelerations (comfort criteria for pilots and passengers). Figure 8 illustrates the impact of the law on the placement of aircraft rigid and bending modes, while not impacting other structural modes (above 12 rad/s). Controller modes around 15 rad/s fulfil the roll-off constraint.
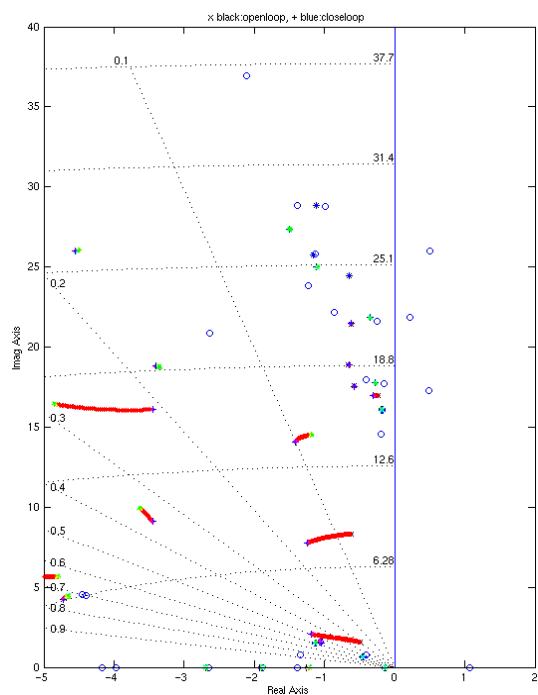

Fig. 8: Root locus showing the impact of the H∞ control law on poles placement: blue x are open-loop aircraft poles, green x are controller poles, black + are closed-loop poles final position.

6. FULLY INTEGRATED MULTI-OBJECTIVES H∞ DESIGN

6.1 *Description*

Objective of this second integrated approach is firstly to avoid the 2 steps process, and secondly and more important to act on both rigid and bending mode to alleviate the loads. Handling qualities are therefore expressed directly in H∞ along with loads constraints

expressed not only at frequens around the bending mode, but for any frequency from 0 to 2 Hz..

6.2 *H∞ design schema*

The following requirements are then expressed using dedicated H∞ expressions and gathered in the H∞ schema of figure 9:
o HQ and Loads are integrated in a common transfer function dedicated to minimising the impact of wind on both the bending and rigid modes:

$$\left\| W_{LP/BP} \cdot \left(\frac{Nz_i}{wind} \right) \right\|_{\infty}$$

with $W_{LP/BP}$ either a low-pass or a band-pass filter, depending on which Nz is considered.

Others are kept as in method n°1:
o Guaranteeing stability margins: $\|T\|_{\infty}$ with T the complementary sensitivity function.
o Robustifying the control to modes frequency variations δf: $\left\| \frac{Nz}{\delta f} \right\|_{\infty}$

o Preventing gains at high frequencies $\left\| G.(1+GK)^{-1} \right\|_{\infty}$.

o Avoiding gains on some actuators at low frequencies $\left\| W_{LP}.G.(1+GK)^{-1} \right\|_{\infty}$.
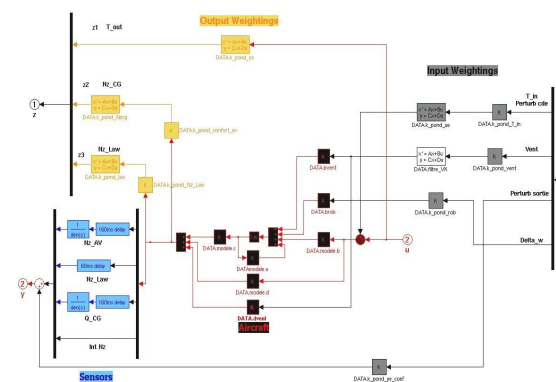

Fig. 9: H∞ schema for multi-objectives design method n°2.

6.3 *Method evaluation*

This one step fully integrated approach allows to:
- Alleviate loads acting on both bending mode & rigid mode,
- Optimise the handling qualities behaviour in turbulence.
Nevertheless difficulties are encountered:
- There is a loss of control on the handling qualities behaviour in pilot manoeuvres, as handling qualities performances are now expressed in H∞ which is an indirect formulation of the specifications, better expressed by a pole placement constraint.
- The tuning of handling qualities is very sensitive to the weightings $W_{LP/BP}$ introduced in the H∞ schema. Experience is needed to better handle these weightings.

6.4 *Performances evaluation*

Figures 10 and 11 illustrate the performances obtained with this approach. Tuning was made with less bending-mode damping compare to figures 6 and 7. The counterpart is a bigger influence on the rigid mode, whose frequency is shifted from ~0.2 Hz to ~0.5Hz as seen on the first plot of figure 11. This proves the influence of the integrated approach on the rigid modes, even if this influence is not fully mature yet. This is very promising in the perspective of optimising the compromise between rigid bandwidth and bending mode alleviation. All other constraints were fulfilled as in the previous 2 steps approach.
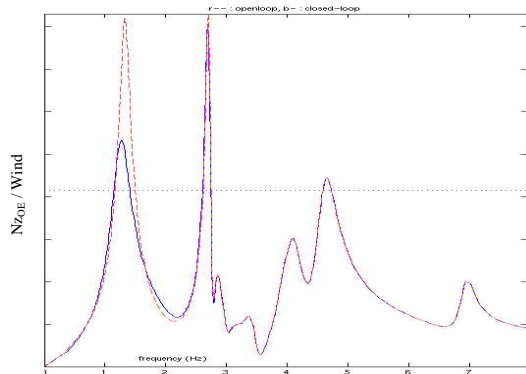

Fig. 10: Transfer function between wind and longitudinal acceleration at outer engines position: open loop in red, closed-loop in blue.

7. ON BOARD IMPLEMENTATION

Coding of any on-board function has to be done using SAO, a D0178B qualified C-code generator, which automatically produces, and implements on-board flying computers the codes coming from engineering system block diagrams. This generator is compatible with all Airbus validation tools. It is very similar to Simulink[tm], but with a very limited library of elementary functions, such as multiplier, divider, sum, logical operators, delays, 1st and 2nd order SISO filters, and limiters. It does not permit to handle vectors or matrixes, only scalars.

Multi-objectives control laws obtained with method n°1 or method n°2 are MIMO state-spaces systems. Coding such control laws with the existing SAO library may become complex regarding the number of inputs and outputs or the order of the law. Works to come will investigate order reduction (Puyou, *et al.*) different coding solutions compatible with available memory and numerically stable.

8. CONCLUSION AND PROSPECTS

The paper presents on going activities in Airbus regarding integrated multi-objectives flight control laws. Such laws are expected to really improve the design process by avoiding numerous design/validation iterations. These integrated approaches reduce conservatism by avoiding decoupling constraints, which limit the achievable performances. On the contrary the integrated design allows pushing further the requirements, such as enhanced passenger protection or comfort. Preliminary evaluations show a real improvement compared to the traditional methods or past works.

Future works will consist in more in-depth evaluation of the approaches described in this article to gain experience on these new methods. This includes evaluation on simulator or in flight with pilots, control law order reduction, interpolation to cover the entire flight domain, coding architecture and numerical stability.
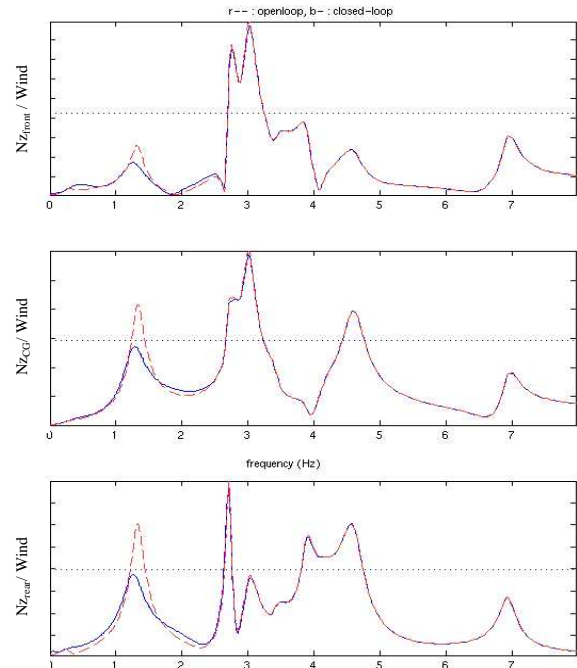

Fig. 11: Transfer functions between wind and longitudinal acceleration at different positions along the fuselage: open loop in red, closed-loop in blue.

9. ACKNOWLEDGEMENTS

REFERENCES

Jeanneau, M., N. Aversa, S. Delannoy and M. Hockenhull (2004). *Awiator's study of a wing load control: design and flight test results.* 16th IFAC Symposium on Automatic Control in Aerospace. St. Petersburg, Russia. 14-18 June.

Ferreres, G. (1999). *A practical approach to robustness analysis with aeronautical applications*, Kluwer Academic Publisher.

Puyou, G., G. Ferreres, C. Chiappa, and P. Menard (2004). *A multiobjective method for flight control law design.* AIAA GNC conference. Providence, USA. August.