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AEROELASTIC ROLE IN THE ROAD TO A FULLY AUTOMATED REFUELLING SYSTEM

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Abstract: AIRBUS Defence and Space (AIRBUS-DS) has successfully designed, manufactured, and certified the Aerial Refuelling Boom System ARBS (or "Boom") that is nowadays extensively operated by different Air Forces. The Boom is a deployable and retractable flexible beam hanged from the rear part of a taker-aircraft fuselage through which fuel can be transferred to a receiver aircraft at high fuel rates (Figure 1).

The existing version of the AIRBUS-DS Boom system is a fly-by-wire device with flight control laws (FCLs) adapted to each flight phase and Boom configuration. These FCLs improve the flight mechanics handling qualities, mitigate the coupling of the flexible modes with the rigid motion, and allow the Boomer to perform high precision contacts with limited effort in calm weather or even in light-to-moderate atmospheric turbulence conditions.

Next step on the AIRBUS-DS Boom project points towards improving the robustness and precision of the refuelling operation by including automatic controlled-by-computer Boom motion. The intervention of the Boomer could be ideally reduced to emergency or out-of-control situations. All the engineering activities launched to support this project are embedded into the Automated Air-to-Air Refuelling (A3R) program.

This paper summarizes the aeroelastic activities performed by AIRBUS-DS for supporting the design of the A3R Boom system, a high-precision automatic operation of the Boom with reduced human intervention. The Boom aeroservoelastic model used in the A330-MRTT Certification Phase has been revisited to include additional terms that are needed to increase the accuracy on the aeroelastic-related parameters that the A3R operation demands. In particular, the static aeroelastic deformation will depend on the rigid body excursions which are not well predicted by classical methods.

Theoretical results obtained from an enhanced non-linear aeroservoelastic model show good matching with ad-hoc data-gathering flight tests. This model will be used to support the A3R flight control laws design and to improve the appearance of the Boom flexibility in the Boom simulator.

Figure 1 An A330-MRTT tanker aircraft while refuelling to another A330-MRTT acting as receiver.

1 INTRODUCTION

Airbus Derivatives is a business line of AIRBUS-DS that is specialized in the conversion of existing AIRBUS aircrafts for including new capabilities: in-flight refuelling, VIP transport, medical evacuation, surveillance and control with a dome-struts system (AWACS), Military Patrol Versions, etc. In particular, the in-flight refuelling is today a successful product that is offered via the A330-MRTT (Multi-role Tanker Transport) platform, a derivative aircraft from the Airbus A330-200. As sketched in Figure 2, the A330-MRTT is today capable to supply fuel by installing the package of underwing pods plus Boom (MRTT version) or the package composed of underwing pods plus a fuselage refuelling unit (Future Strategic Tanker Aircraft FSTA version). Besides this, the A330-MRTT has the role of receiver aircraft through the Universal Aerial Refuelling Receptable Slipway Installation UARSSI.

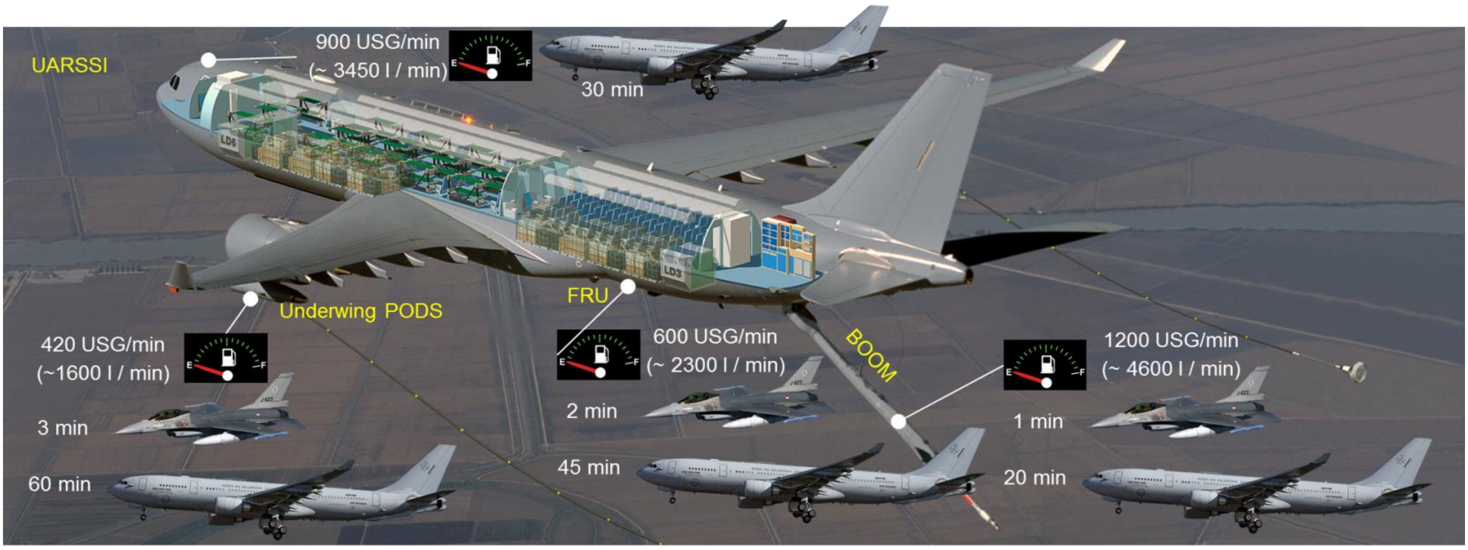


Figure 2 A330-MRTT (Multirole Tanker Transport)

The Aerial Refuelling Boom System (ARBS or "Boom") is a deployable and retractable mast-beam system installed in the rear fuselage of the tanker aircraft (Figure 3). The Boom is controlled by the aerodynamic forces generated by two V-shaped ruddervators which symmetric or antisymmetric rotation is commanded by the Boom operator (or "Boomer"), a member of the tanker crew.

Figure 3 Aerial Refuelling Boom System (ARBS) installed in the A310-Demo aircraft

In free-flight, the Boom has three degrees of freedom (Figure 4): roll angle (lateral motion), pitch angle (vertical motion), and telescopic beam extension (❶, ❷, and ❸ in Figure 4 respectively). As sketched in Figure 4, vertical motion is said “gamma” mode (γ-angle, degree of freedom ❷) if the Boom is freely rotating around the pitch axis or “tau” mode (τ-angle) if the Boom mast has contacted with the roll-pitch joint (the fitting that joints the Boom mast to the fuselage) at point A, the pitch rotation is blocked, and the block composed by the roll-pitch joint plus the Boom is rotating around the pivot axis.

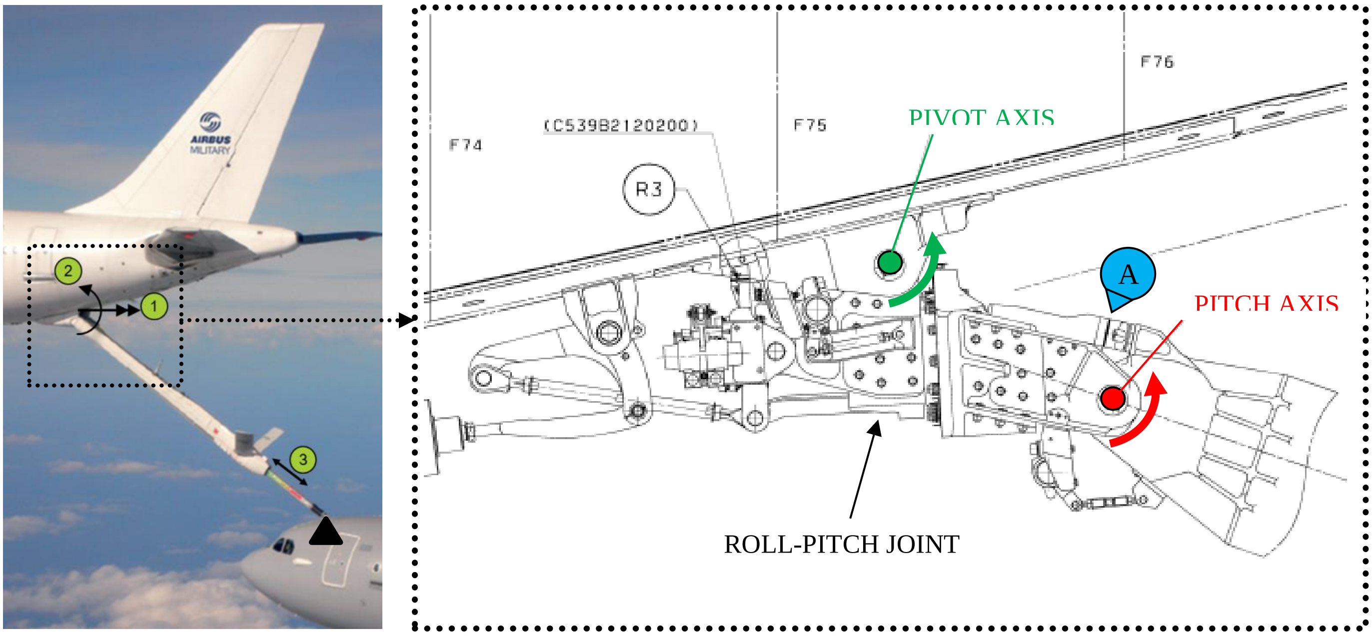


Figure 4 Left figure: Boom deployed with the three degrees of freedom. Right figure: Detail of the roll-pitch joint, the Boom-to-aircraft fitting.

Figure 5 shows the 3D stereoscopic view that is shown in the computer screen of the Boom operator. Orange-coloured contour corresponds to the Boom control envelope (unconnected-to-receiver free flight) while blue-coloured contour corresponds to the connected-to-receiver Boom envelope. These contours are not drawn in the aircraft onboard screen and are shown just for reference.

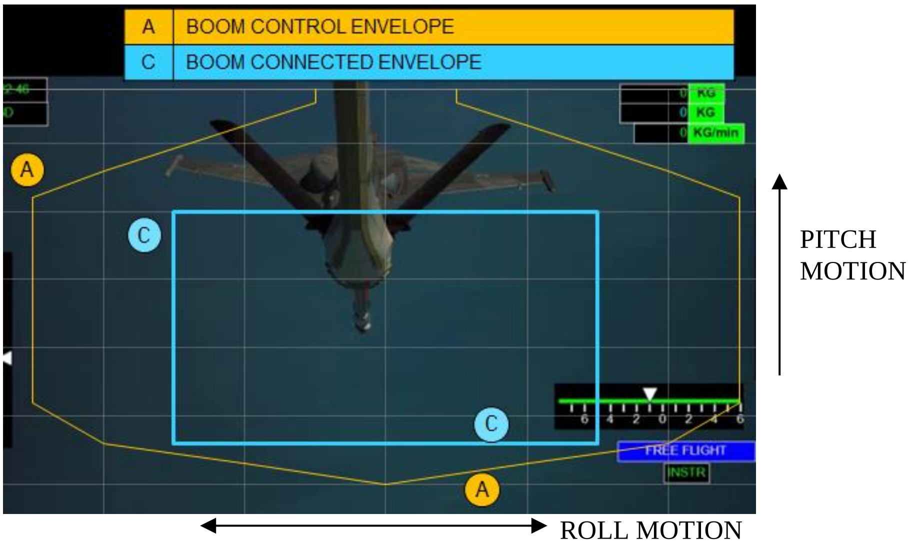


Figure 5 Image of the Boom that is shown in the computer screen of the Boomer. Contour A and C represent the “control envelope” and the “connected envelope” respectively. These contours are only plot for reference and are not shown in the aircraft onboard screen.

The Boom operation itself leads to challenging characteristics from the aeroelastic standpoint:

- Variable geometry configuration: the large roll- and pitch-angle excursions lead to changes on the sweep and dihedral angle of the ruddervators (Figure 6).
- Variable stiffness: as the telescopic beam is being retracted/extended, the position along the mast of the mast-to-telescopic fittings changes and the global stiffness of the Boom as component changes (Figure 7).
- Variable mass: fuel OFF and ON configurations.
- Variable boundary conditions: clamped to the tanker (Boom in stowed condition), free flight, and connected-to-receiver configuration.
- Structural nonlinearities: the transition from γ- to τ-mode (Figure 4) implies a sudden change of the boundary condition that is represented by a stiffness local nonlinearity.

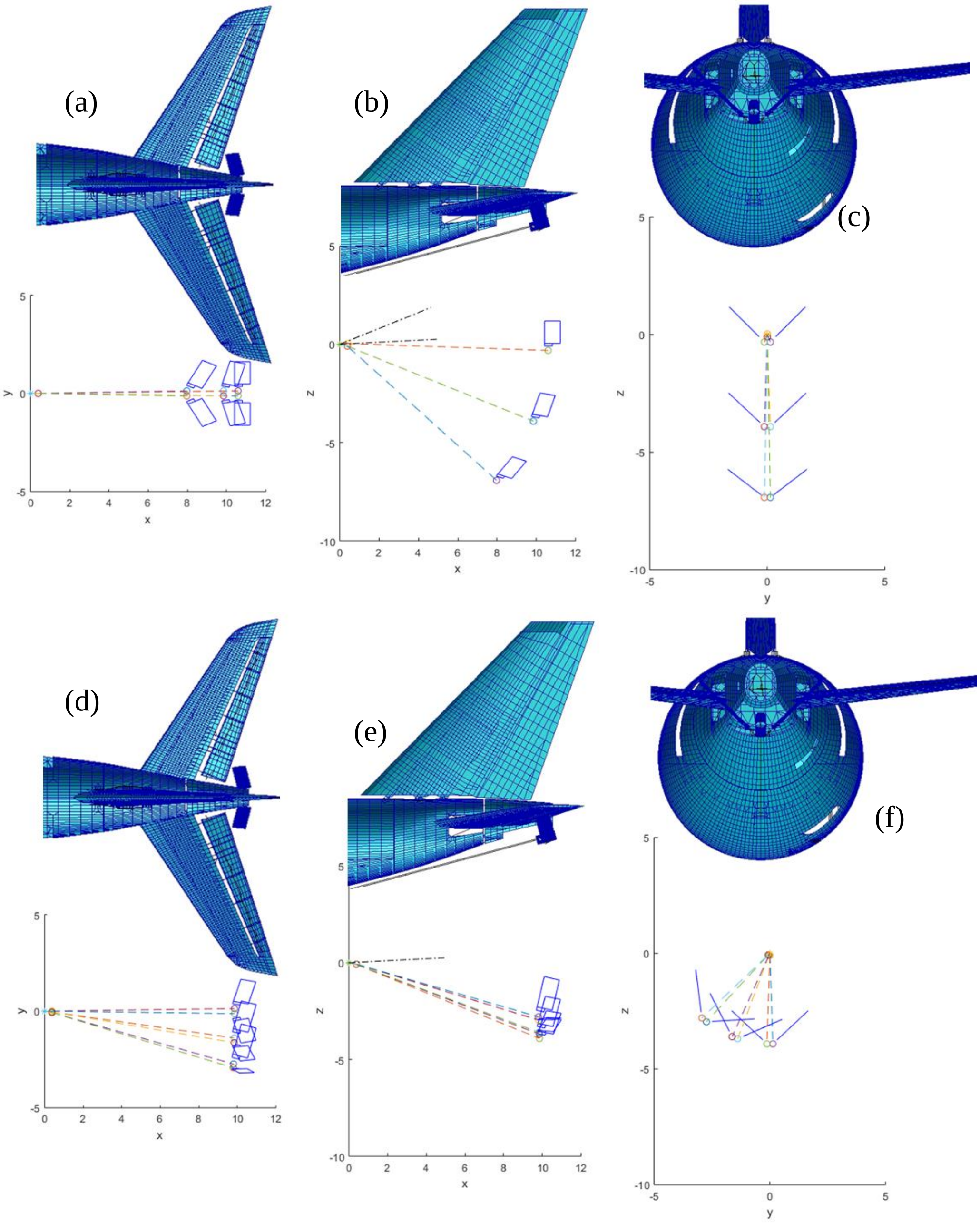


Figure 6 (a) shows ruddervators planform for different pitch angles shown in (b) and (c). The ruddervator sweep angle changes with the Boom pitch angle. (d), (e), and (f) corresponds to xy-, xz-, and yz-view of the ruddervators planform when the roll angle changes; both sweep and dihedral angles vary with the Boom roll.

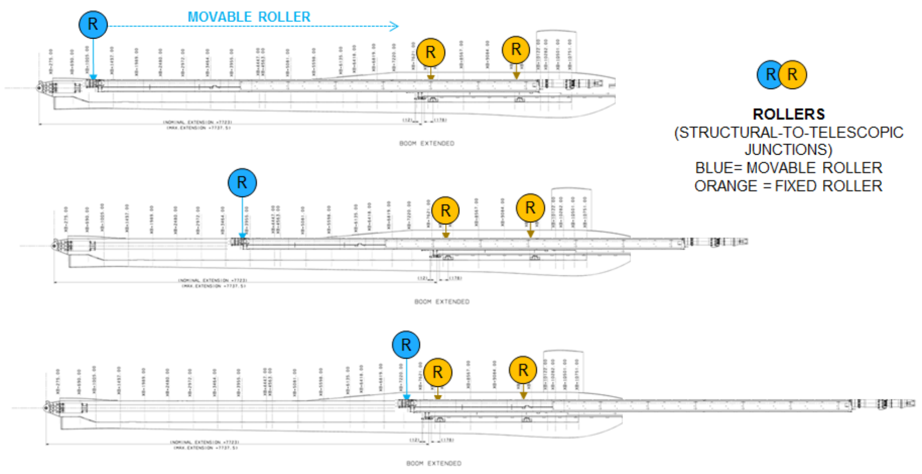


Figure 7 Schematic view of how the rollers (mast-to-telescopic fittings) evolve as the telescopic length changes.

Changes on the stiffness, mass, and the boundary conditions lead to variation of normal modes frequencies and shapes as the Boom performs the refuelling operation. Figure 8 shows how the unconnected-to-receiver normal modes frequencies change as a function of the Boom telescopic beam extension.

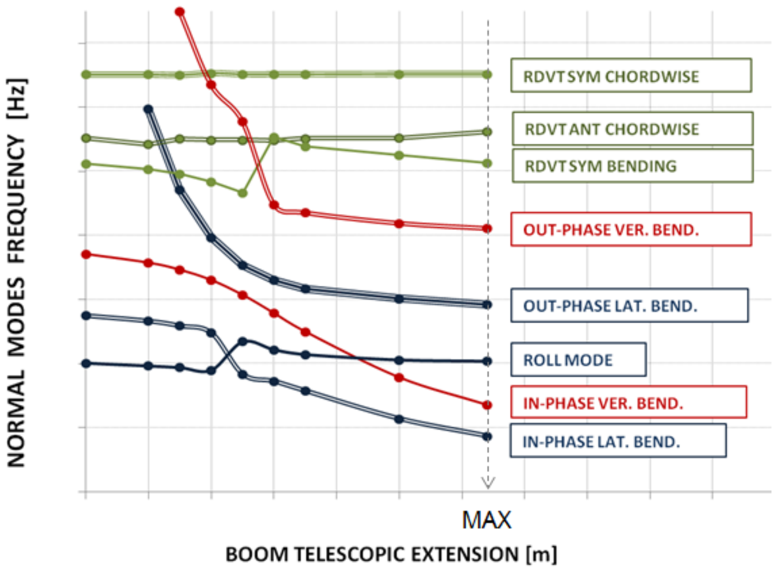


Figure 8 Normal modes frequencies as function of the telescopic beam extension.

This section has briefly described the Boom system, showing the real-time changing properties that are inherent to the Boom operation. Certification analyses did cover all these Boom configurations in an accurate and conservative way.
However, The Boom design continues evolving and the computer-aided refuelling operation, with a reduced human intervention, is one of the key points that AIRBUS-DS is currently developing. For this automated refuelling, the accuracy of the Certification models is sometimes not enough for securing a safe and reliable operation. In particular, the Boom nozzle location, which is one of the main parameter for the closed-loop flight control laws in the A3R operation, is affected by the flexibility of the Boom and therefore the reliability of the A3R system depends on how accurate the Boom flexibility is included in the loop.
Next section will detail all the flight tests and calculations done in the AIRBUS-DS Structural Dynamics and Aeroelasticity Department to improve the Boom aeroelastic model that supports the Boom Automated Air-to-Air (A3R) refuelling operation.

2 AEROELASTIC MODELS OF THE BOOM

2.1 INTRODUCTION

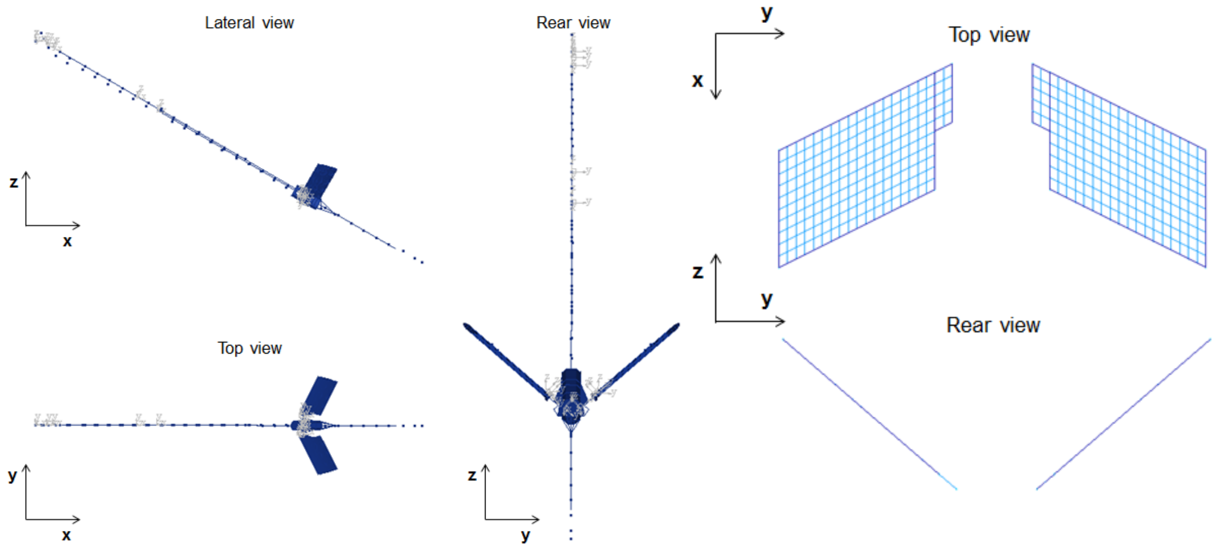
The aeroservoelastic calculations of the Boom have been conducted by using different levels of complexity according to the event that needed to be reproduced. Three models have been considered:

1. *Classical linear aeroelastic model*, valid for most of the Certification-phase calculations: flutter, aeroservoelasticity (including flight control laws FCLs filters design), gust encountering, low-intensity impacts, etc.
2. *Non-linear Boom aeroelastic model*, which is able to reproduce the roll-pitch joint concentrated structural non-linearity linked to the γ- to τ-mode transition (Figure 4, reference [3]). This transition only occurs when the Boom is rotated up for separating from the receiver aircraft in a safe separation assessment (SSA) maneuver.
3. *Enhanced non-linear Boom aeroelastic model*, which is an evolution of the previous non-linear model to match flight dynamics behavior and to increase the accuracy when predicting the Boom mast flexible deformation. This is the model explicitly developed for the A3R operation and its development has been supported by additional ad-hoc flight tests.

The linear and non-linear aeroelastic models are described in next two subsections 2.2 and 2.3. The enhanced non-linear model will be detailed in section 4 after describing the flight tests (section 3) that have been used for characterizing the terms retained to improve the model to the standards required by the automated operation.

2.2 CLASSICAL LINEAR AEROELASTIC MODEL

A classical linear aeroelastic model has been used for the Boom Aeroelastic and Dynamic Loads certification analyses. The stiffness and mass properties are modelled with a Finite Element Method (FEM) model (see MSC.NASTRAN model in Figure 9a) while the unsteady aerodynamics is based on the subsonic Doublet-Lattice Method (DLM) (Figure 9b). Aerodynamic panel-level corrections have been included to account for different effects as fuselage wake (when Boom in stowed position), ruddervators aerodynamic effectiveness, transonic effects (shock waves), or ruddervators high angle-of-attack stall condition.



a. Boom FEM model in MSC.NASTRAN

b. Doublet-Lattice unsteady aerodynamics model.

Figure 9 Classical linear aeroelastic model

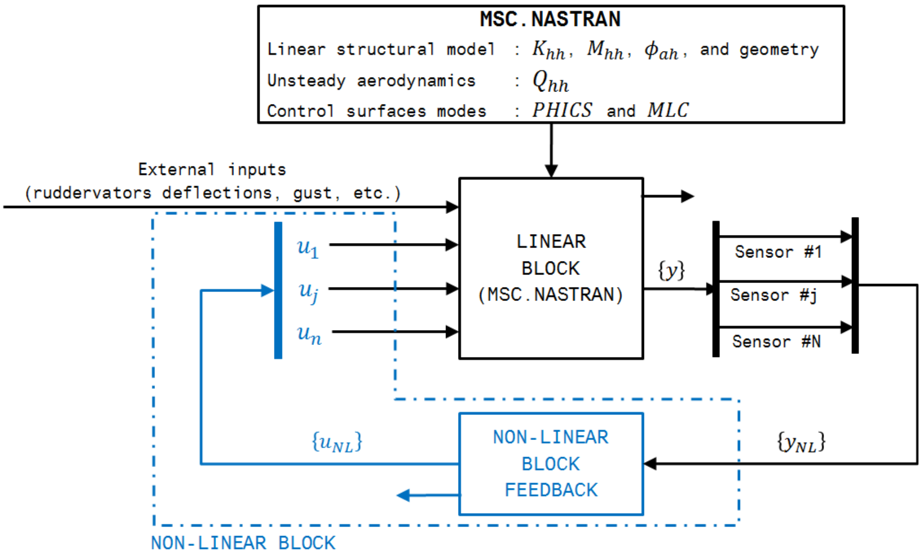
The linear aeroelastic model is no longer valid when structural or aerodynamic nonlinearities appear as relevant in the Boom operation. For example, the transition from γ- to τ-mode (explained in section 1) implies a contact-type boundary condition change that is inherently non-linear. This was the reason to develop the non-linear model described in next section.

2.3 NON-LINEAR BOOM AEROELASTIC MODEL

The calculation of the aeroservoelastic response due to external excitations (control surface commands, gusts, etc.) in the presence of nonlinearities is obtained using the Increase Order Method IOM ([4]), which consists on adding the non-linear contribution, calculated via convolution integrals, to the linear aeroservoelastic response of the system (Figure 10), i.e.,

$$\{y(t)\} = \{y_L(t)\} + \int_0^t [y_{LU}(t-\tau)]\{u_{NL}(\tau)\}\, d\tau$$

where $\{y(t)\}$ is the system response (linear plus non-linear), $\{y_L\}$ is the response of the system linear block (with the non-linear block disconnected) to the external inputs (ruddervators commands, gusts, etc.), and $[y_{LU}]$ is a matrix with the response of the system linear block to impulse-type excitations on the input variables to the linear block $\{u_{NL}\}$. This mathematical formulation has been coded in the software DYNRESP ([6]).
As example, DYNRESP has been used for assessing the non-linear stiffness at the roll-pitch joint when transitioning from γ- to τ-mode that has been mentioned before, obtaining accurate results after comparing with flight test data ([3]). Besides this particular application on the Boom, this convolution-based formulation has been extensively used by AIRBUS-DS to solve different types of non-linear problems ([4] and [5]).



K_{hh} Generalized stiffness matrix
M_{hh} Generalized mass matrix
ϕ_{ah} Normal modes matrix

$\{y\}$ System output
$\{y_L\}$ Linear block response to linear inputs (ruddervators deflections, gusts, etc.)
$\{y_{NL}\}$ Non-linear block input
$[y_{LU}]$ Linear block response to u_j impulse-type inputs.

$\{u_{NL}\}$ Non-linear block output that are input to the linear block.

$$\{y(t)\} = \{y_L(t)\} + \int_0^t [y_{LU}(t-\tau)]\{u_{NL}(\tau)\}\, d\tau$$

Figure 10 Aeroelastic model for including non-linearities. The linear plant is complemented by introducing non-linearities through the convolution theory. For this purpose, the impulse-type response of the linear system to the non-linear items (vector $\{u_{NL}\}$) needs to be calculated (matrix $[y_{LU}]$).

3 FLIGHT TEST DATA GATHERING FOR DEVELOPING THE ENHANCED NON-LINEAR BOOM AEROELASTIC MODEL

Two flight tests have been specifically performed to gather information on the Boom rigid and elastic behavior to support the development of the enhanced non-linear aeroelastic model. Boom was installed in the A310-Demo platform (Figure 11), the aircraft that is currently used in AIRBUS-DS Getafe for testing all the Boom developments, mainly new Boom flight control laws.

Figure 11 Refuelling Boom deployed flying in the A310-Demo test bed.

Steady, quasi-steady, and dynamic conditions were tested in flight by defining roll/pitch sequences reached by moving the ruddervators. Figure 12 shows one of these roll/pitch sequences: the Boom tracked the points sequentially from 0 to 9 at low speed (quasi-steady condition with low/null excitation of flexible normal modes), maintaining a 5-seconds steady condition on each point (steady). In other sequences similar to the one depicted in Figure 12, the Boom motion was required at maximum ruddervators rate deflection, obtaining response of the Boom flexible normal modes (dynamic condition).

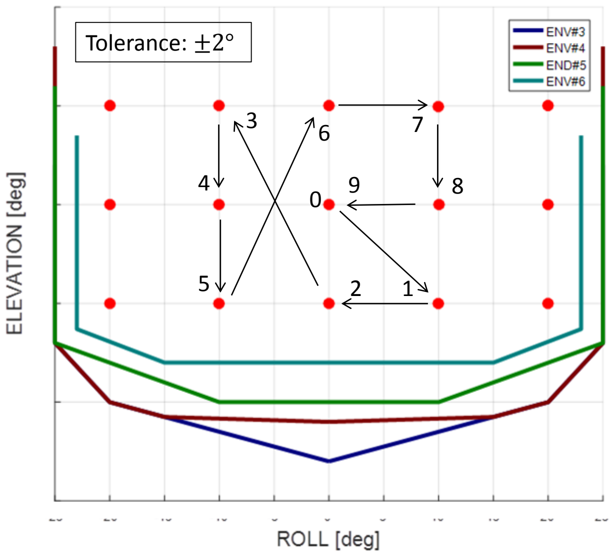


Figure 12 Example of roll/pitch sequence followed by the Boom during the flight tests.

Figure 13 shows the 7 accelerometers selected to obtain information from these data-gathering flight tests, all of them extracted from the accelerometers that were previously installed for the Boom flight flutter tests. Besides these accelerations, the roll and pitch rotation angles, the position of the mast tip ("fairing position" in Figure 13), and the nozzle position ("nozzle position" in Figure 13) were required to be tracked.

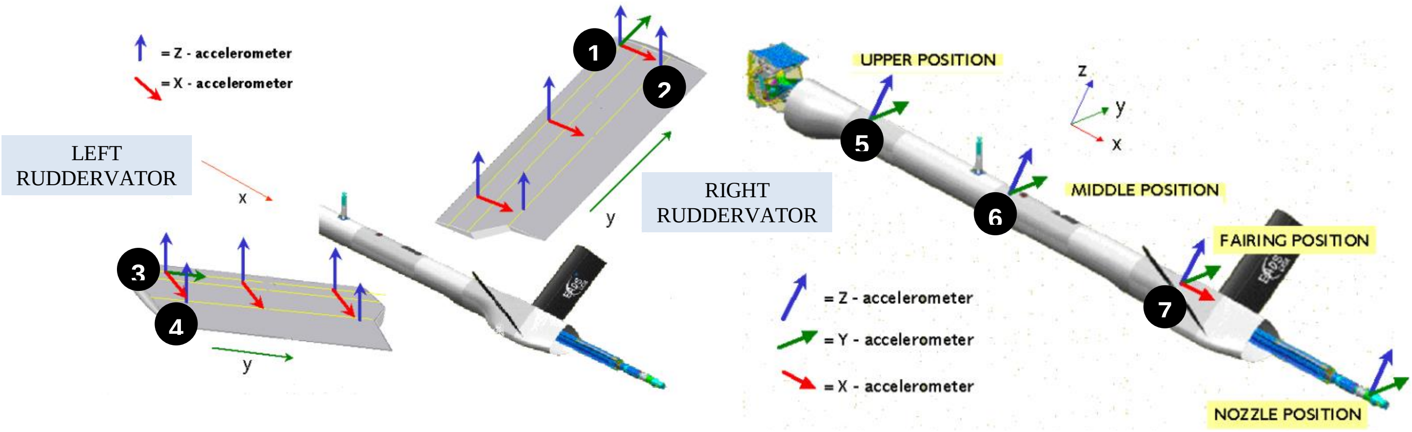


Figure 13 Boom accelerometers installed for Boom flight flutter tests and the 7 accelerometers selected for the data-gathering flight tests described into this section. 1: Right Ruddervator front spar x-,y-, and z-axis; 2: Right Ruddervator rear spar z-axis; 3: Left ruddervator front spar x-, y-, and z-axis; 4: Left ruddervator rear spar z-axis; 5: Mast upper position y- and z-axis; 6: Mast middle position y- and z-xis; 7: Mast fairing position x-, y-, and z-axis.

Figure 14 shows the time-histories of the relevant Boom parameters as directly obtained from the in-flight recorded signals when the Boom followed the sequence depicted in Figure 12. It is seen how pitch and roll angles evolve as a consequence of symmetric and antisymmetric deflections of the ruddervators. If the ruddervators deflection shown in this figure is introduced into a classical aeroelastic model, the pitch and roll angles may not be probably coincide with those obtained from flight tests, mainly because the classical aeroelastic models lack of first-order terms that are relevant in flight mechanics. Next section will explore which terms are relevant to obtain the enhanced aeroelastic model that provides higher accuracy.

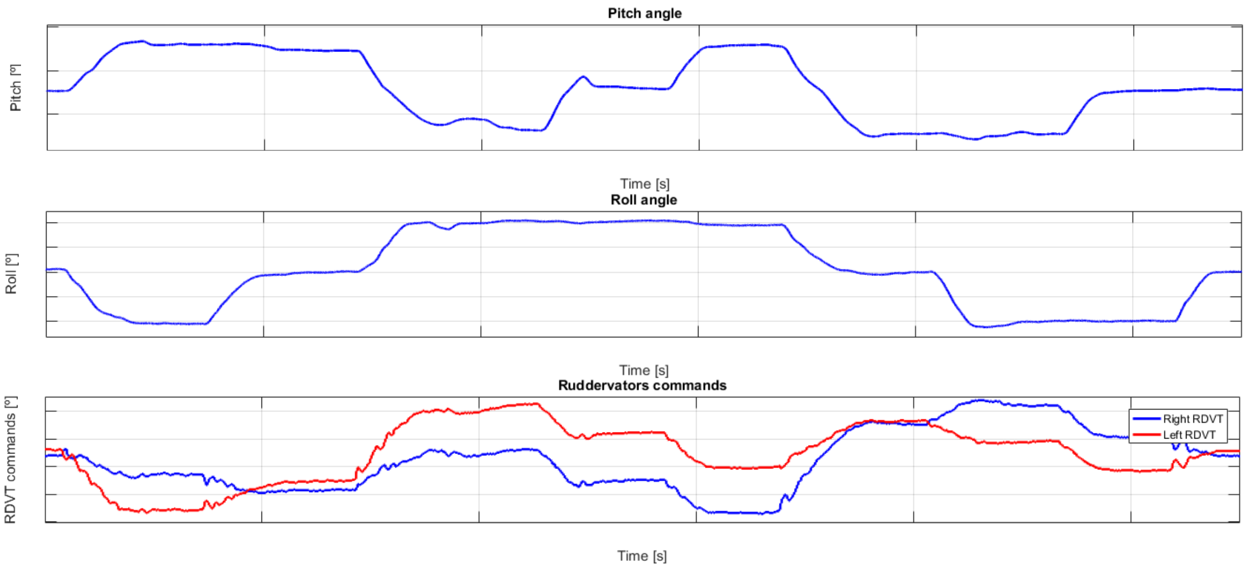


Figure 14 Pitch and roll angle evolution as consequence of ruddervators deflection.

4 ENHANCED NON-LINEAR BOOM AEROELASTIC MODEL

Previous section has detailed the models used for the dynamic loads and aeroservoelastic calculations of the A330-MRTT. Safety was the most valuable characteristic of these analyses and accuracy on predicting the Boom rigid body motion, the static aeroelastic deformation, etc. was sometimes sacrificed in lieu of safe, reliable, and conservative results. Besides this, nowadays industry classical aeroelastic methods lack of first-order terms that need to be retained if the simulations are intended to match large rigid body motions, to adjust the flight dynamics model, or even to obtain certain accuracy on the aeroelastic deformation. The enhanced model herein described has been explicitly developed to increase the accuracy of the Boom aeroelastic model by adding the effects depicted in Table 1. Next sections describe one by one each effect.

Effect	Reason	How?
Gravity effects	Gravity forces/moments do not change if small displacements are assumed. However, the Boom has large rigid-body displacements that lead to changes on the gravity application point that in turn leads to gravity-related moments with respect to the roll-pitch joint.	Feedback forces as function of the pitch and roll angle measured by virtual sensors in the aeroelastic model.
Flow detachments (stall and high speed)	The unsteady aerodynamic forces on ruddervators are based on Doublet-Lattice, a linear method that does not capture flow detachment associated to stall conditions. Because of the large rigid body rotations of the Boom, the ruddervators are sometimes working close to the stall angle.	Feedback forces as function of the ruddervators deflection measured by virtual sensors in the aeroelastic model.
Incremental aerodynamic drag	The aerodynamic drag of the Boom mast and telescopic beam exhibits incremental changes when changing roll and/or pitch angles. The drag is no considered in classical linear aerodynamic models as the Doublet-Lattice.	Feedback forces as function of the pitch and roll angle measured by virtual sensors in the aeroelastic model.
Ruddervators variable geometry	As Boom changes the rigid-body pitch angle, the ruddervators sweep angle is changing. As Boom changes the rigid-body roll angle, the ruddervators dihedral also changes. The classical Doublet-Lattice Method does not change the reference geometry and the real-time variable-geometry characteristic of the ruddervator is therefore not captured.	Feedback forces as function of the pitch and roll angle measured by virtual sensors in the aeroelastic model.
Boom asymmetries and damping	Asymmetries on manufactured Booms, high Mach number and damping need of additional correction factors that have been obtained after analyzing the flight test data.	Ruddervators deflection is factorized to account for asymmetries, etc.

Table 1 Additional effects included into the “enhanced” non-linear aeroelastic model.

4.1 GRAVITY EFFECTS

Figure 15 shows how an initial equilibrium state of the Boom (state labelled as “❶”, typically roll 0 degrees and elevation 30 degrees while waiting for the contact with the receiver) is altered after deflecting the ruddervators. The rotation of the Boom ruddervators generates incremental unsteady aerodynamic forces that rotate the Boom around its two degrees of freedom (pitch/roll) up to reach a new static equilibrium position (state labelled as “❷”).
In this Boom rigid-body motion, the gravity forces exhibit changes that are not captured by classical linear aeroelastic methods. More specifically, the rigid-body motion leads to vertical and lateral displacements of the centre of gravity, moving the application point of the gravity force with respect to the roll-pitch joint which in turn leads to global gravity-related moments with respect to the roll-pitch joint.
These incremental gravitational moments are introduced into the Boom aeroelastic model through feedback forces as function of the pitch and roll angle dictated by a virtual sensor in the model.

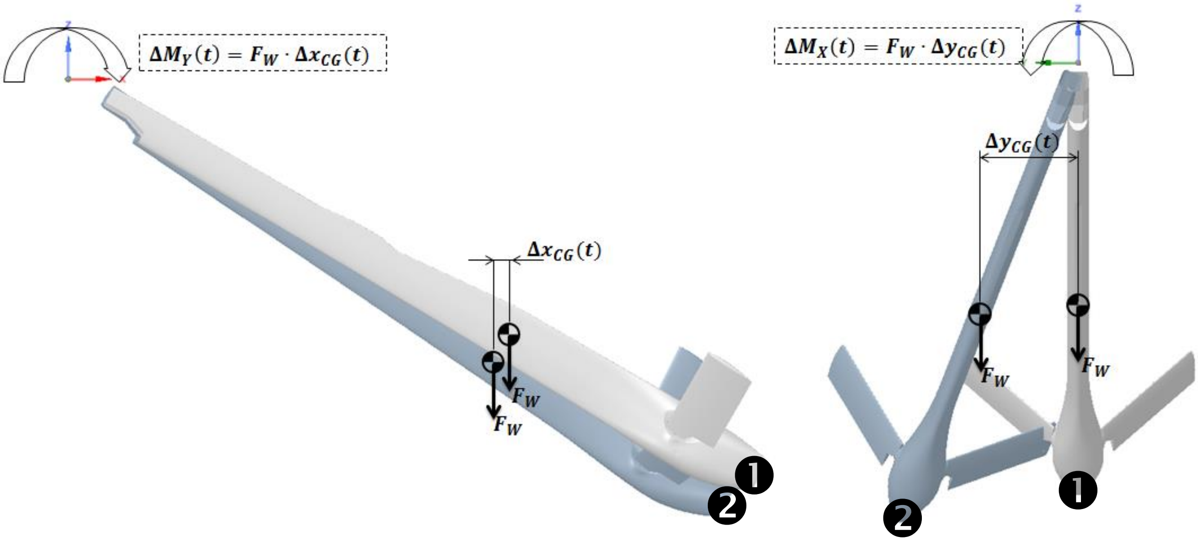


Figure 15 Schematic representation of how both pitch and roll angles changes modify the gravity effects including incremental forces on the dynamic motion of the Boom with respect to an initial steady state.

4.2 AERODYNAMIC NONLINEARITIES: HIGH ANGLE-OF-ATTACK FLOW DETACHMENT

Boom ruddervators are treated as lifting-type surfaces with unsteady aerodynamic forces/moments calculated with the classical Doublet-Lattice Method (DLM), a linear method that does not capture non-linear effects as flow detachment associated to stall conditions.
Because of the large rigid body excursions of the Boom, the ruddervators are sometimes working close to the stall angle. In particular, downward pitch-angle motions (γ-angle 40 [deg] in Figure 16) lead to high angle of attack on the ruddervators (pushing down) that in turn produces flow detachment in ruddervators (❶ in Figure 16, photo from wind tunnel tests). Besides this, and for high Mach number flight points, the fairing of the structural mast close to the ruddervators location (❷ in Figure 16) also exhibits flow detachments.

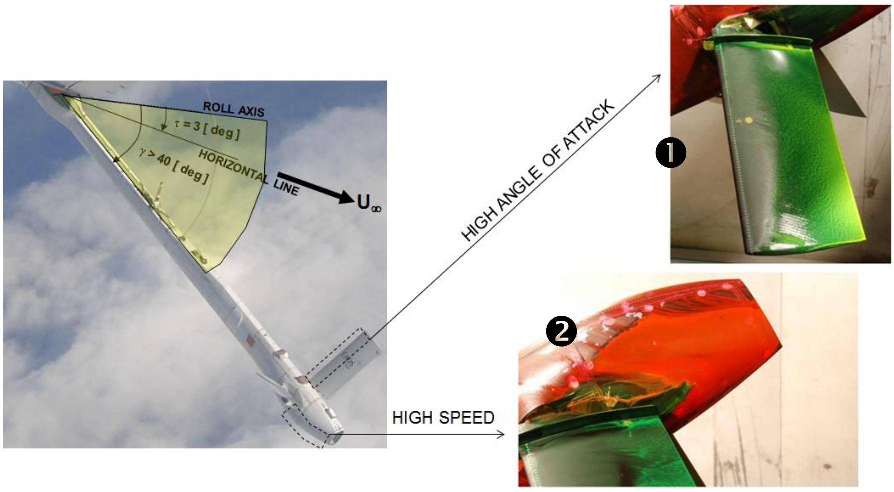


Figure 16 High angle-of-attack and high-speed flow detachments that occur at the Boom ruddervators and structural mast fairing. Image obtained from wind tunnel tests.

A non-linear closed-loop system has been designed to include these stall-related effects in the aeroelastic model. The deflection of each ruddervator is measured thru a virtual sensor and the total lift is conveniently adjusted by applying additional deflection-dependent feedback forces that reduce the ruddervator efficiency. The ruddervators stall onset angle is determined from flight test data and depends on Boom configuration and flight point.

4.3 INCREMENTAL AERODYNAMIC DRAG

Figure 17 shows the forces and moments that determine the steady state equilibrium position of the Boom in a vertical plane. It is assumed roll zero and the Boom is therefore located in the aircraft symmetry plane. The weight tends to rotate down the Boom while the aerodynamic drag has an opposite effect and, depending on the targeted pitch angle, the ruddervators shall push up or down. In normal operation, with pitch angles between 25 and 35 [deg], the ruddervators should push down (as sketched in Figure 17).
When the Boom changes this equilibrium state, varying pitch and/or roll, the aerodynamic drag will have variations and there appear incremental forces that should be included into the aeroelastic response. The incremental drag forces are modelled through feedback forces linked to a virtual sensor that detects the Boom attitude in the aeroelastic model. These forces depend on the flight point (mainly dynamic pressure and Mach number) and their values are obtained from flight test data.

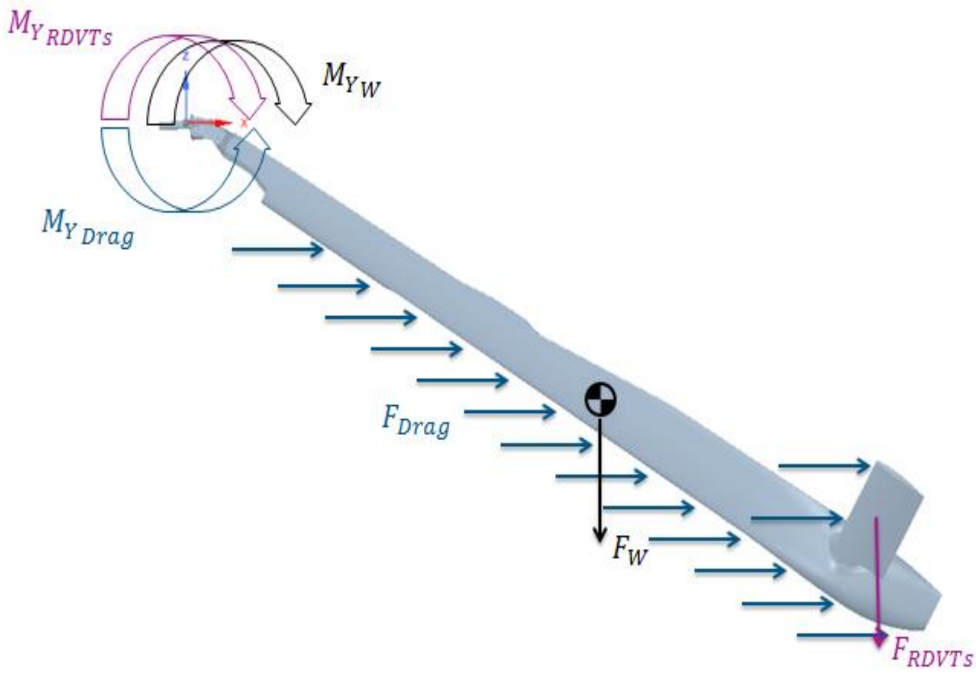


Figure 17 Equilibrium of forces acting on the Boom in the symmetry plane (roll zero). The drag represented is the steady one; however, as the pitch and roll angle changes there appears incremental drag that affect to the dynamic motion with respect to the steady state initial condition.

4.4 RUDDERVATOR VARIABLE GEOMETRY

Figure 6 has shown how the shape and the sweep and dihedral angles of the ruddervators change as the roll and pitch angles evolve. For example, higher positive pitch excursions increase the ruddervators sweep angle as sketched in Figure 18. However, the classical Doublet-Lattice Method does no change the reference geometry and the real-time variable-geometry characteristic of the ruddervator is therefore not captured.

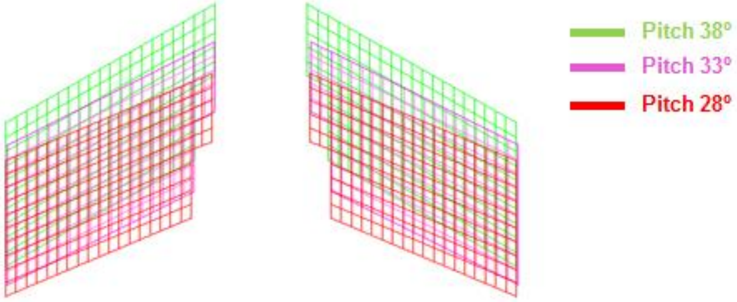


Figure 18 Ruddervators planform as the Boom pitch angle changes. The sweep ruddervators angle together with their surface area changes when the Boom pitch angle evolves.

The influence of the morphing geometry has been checked by comparing the roll angle recorded in a flight test maneuver with the estimated roll angle calculated with the linear aeroelastic model, which does not consider variable geometry. In this maneuver, ruddervators are also deflected symmetrically reaching different pitch angles between 28 and 38 degrees (Figure 19) as the roll evolves. The estimated roll angle from the model has been obtained by running the aeroelastic calculations with the aerodynamics (Doublet-Lattice) computed at three different (but fixed) pitch angles: 28, 33, and 38 degrees. It is seen that, for each stage of the flight, the model that better fits the experimental data is different, being relevant to have the right ruddervator shape for each pitch angle.

As previous effects, the variable-geometry effect is modelled in the aeroelastic model by feedback forces that are function of the pitch and roll angles (measured by virtual sensors in the model) and the flight point (dynamic pressure and Mach number).

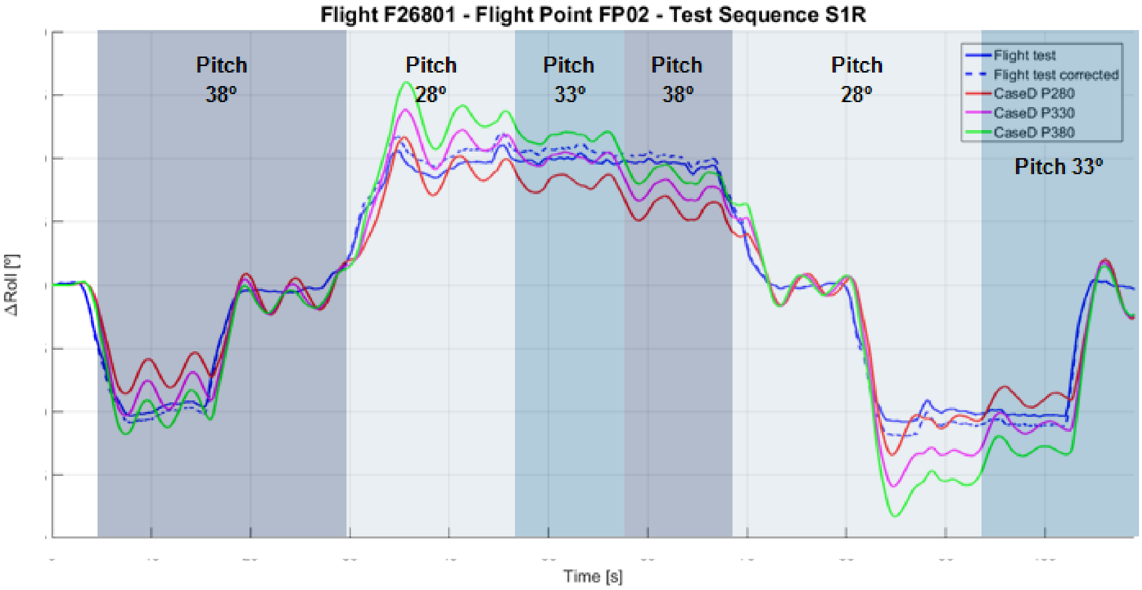


Figure 19 Roll angle evolution measured in flight (blue line) as the Boom is passing through different pitch angles (in the range from 28 to 38 degrees). Red, magenta, and green lines corresponds to the estimated roll evolution calculated with the model at different (but fixed) pitch angles. This comparison highlights the need of considering the ruddervators changing planform as the pitch evolves.

4.5 GEOMETRICAL ASYMMETRIES AND DAMPING

Other second-order effects that improve the matching of the enhanced aeroelastic model with the flight test data are:

1. Boom geometrical asymmetries: flight test data have shown that, to locate the boom at the symmetry plane (roll = 0º), the ruddervators need to be deflected with a certain degree of asymmetry. This asymmetry depends on the Boom attitude (mainly pitch angle), Boom configuration (telescopic beam length, etc.), and flight point.
   The Boom aeroelastic model is fully symmetric and, if this in-flight-measured ruddervators deflection asymmetry is directly imposed at roll zero, the Boom would have a roll deviation (calculated with the model) that does not appear in flight. The way to solve this in the aeroelastic model is, when the Boom is stabilized in the symmetry plane, both left and right ruddervators deflections are changed to its mean value, which allows matching the flight-measured pitch angle while setting the roll to zero, as measured also in flight.

2. Additional damping: flight test data have shown that the Boom response exhibits higher damping than the response calculated with the aeroelastic model. The enhanced aeroelastic model considers feedback damping-type moments at the roll/pitch joint to smooth the Boom rigid body pitch/roll rotations.

5 ADJUSTMENT PROCEDURE OF THE BOOM AEROELASTIC MODEL TO FLIGHT TEST DATA

The enhanced non-linear Boom aeroelastic model has been developed to increase the accuracy of the Certification Phase Boom aeroelastic model by adding the effects explained in section 4 through linear and non-linear closed-loop system in the software DYNRESP ([6]). The data collected in the two flight tests (see section 3) have been used to adjust the closed-loop systems, with the target of ensuring the reliability and representativeness of the aeroelastic model. Once the model matches flight test data and, in particular, is able to capture the flight mechanics behavior, rest of flexibility-related magnitudes can be extracted to support the design of the A3R flight test control laws.

In a first step, the Boom aeroservoelastic model is adjusted to match the large rigid body motions measured in flight during the required roll/pitch sequences. The pitch and roll angles time histories recorded in flight at the roll-pitch joint are compared with the ones obtained by the sensors located at the same position in the simulation model. The effects depicted in previous section have been sequentially added to the model to understand the individual contribution of each one. Next sections describe the relevant terms together with the final matching to the flight tests.

Figure 20 shows the comparison between flight test data and the aeroservoelastic model on the pitch rigid body motion (vertical motion) for a quasi-steady roll/pitch sequence tested (see Figure 12) in four flight point (FP) with the telescopic beam in mid-extended configuration (nominal refuelling condition). The dynamic pressure and Mach number increase from flight point (FP) #15 to FP #18. If none of the effects are included, the aeroelastic model results (black line in Figure 20) are seen to differ substantially from the measured data (blue line). Magenta line represents the simulations after adding the gravity effects, which improves marginally the response. Finally, after adding the rest of effects, the simulation results for pitch angle (red line) match with accuracy the flight test measured pitch. The main relevant effect that contributes to this matching is the incremental drag linked to the pitch angle variation.

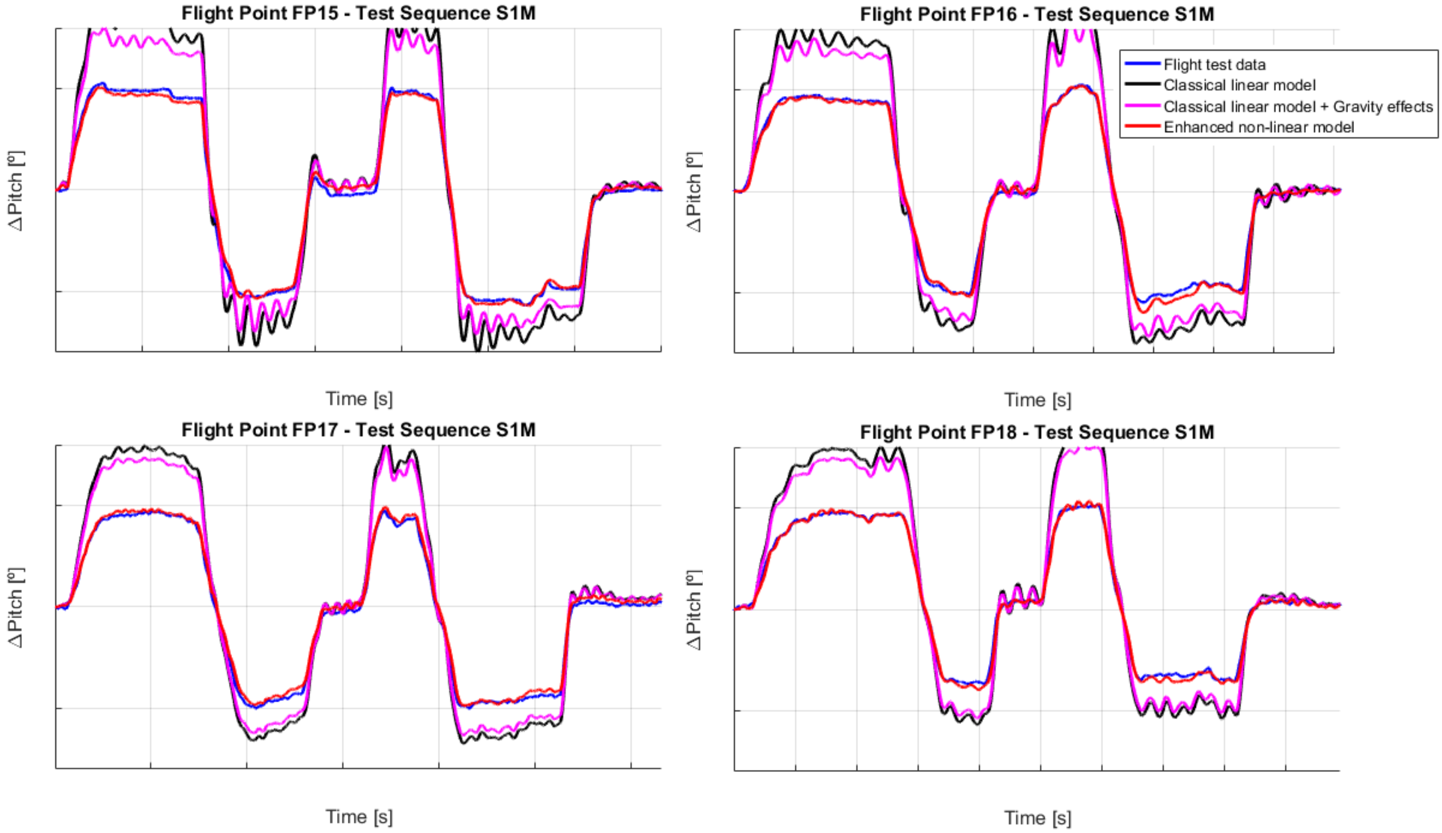


Figure 20 Boom pitch angle evolution caused by quasi-steady symmetric deflections of the ruddervators. Flight test data (blue line) is compared with the following three aeroelastic models: (a) Classical model without corrections (black line), (b) Model including the gravity effects (magenta line), and (c) Model including gravity together with the rest of effects (red line). It is seen the the final approach with all effects included (red line) is certainly closer to the flight test data (blue line).

Figure 21 shows the Boom roll rigid body motion (lateral motion) for the same flight test data sequence depicted in Figure 12. Flight tests measured roll angle (blue line) is compared with the model simulations after including the gravity effects (magenta line) and the rest of effects (red line). For the roll excursions, the gravity effects are much more relevant than for pitch angle variations because of the large centre of gravity variations when the roll angle changes. In fact, simulations without gravity effects lead to unrealistic divergent results. Concerning the rest of effects, the variable-geometry and the incremental drag are the main contributors to the model improvement.

The enhanced non-linear boom aeroelastic model has been adjusted to all the flight points and boom configurations tested in the flight test campaign explained in section 3. In general, similar results to the ones shown in Figure 20 and Figure 21 have been obtained for all the Boom configurations and flight test points covered.

Finally, once the boom rigid body motion is correctly predicted by the aeroservoelastic model, the flexible deformation of the boom system is computed through a post-process of the Boom tip location (nozzle in Figure 3), that is measured by virtual sensors in the aeroelastic model at each simulated test case. This is the relevant information that is today required from the aeroelastic model for supporting the A3R, i.e., how much is affected the nozzle location by the Boom flexibility and how the flight control laws of the A3R will cope with it for performing a reliable and fail-safe refuelling operation.

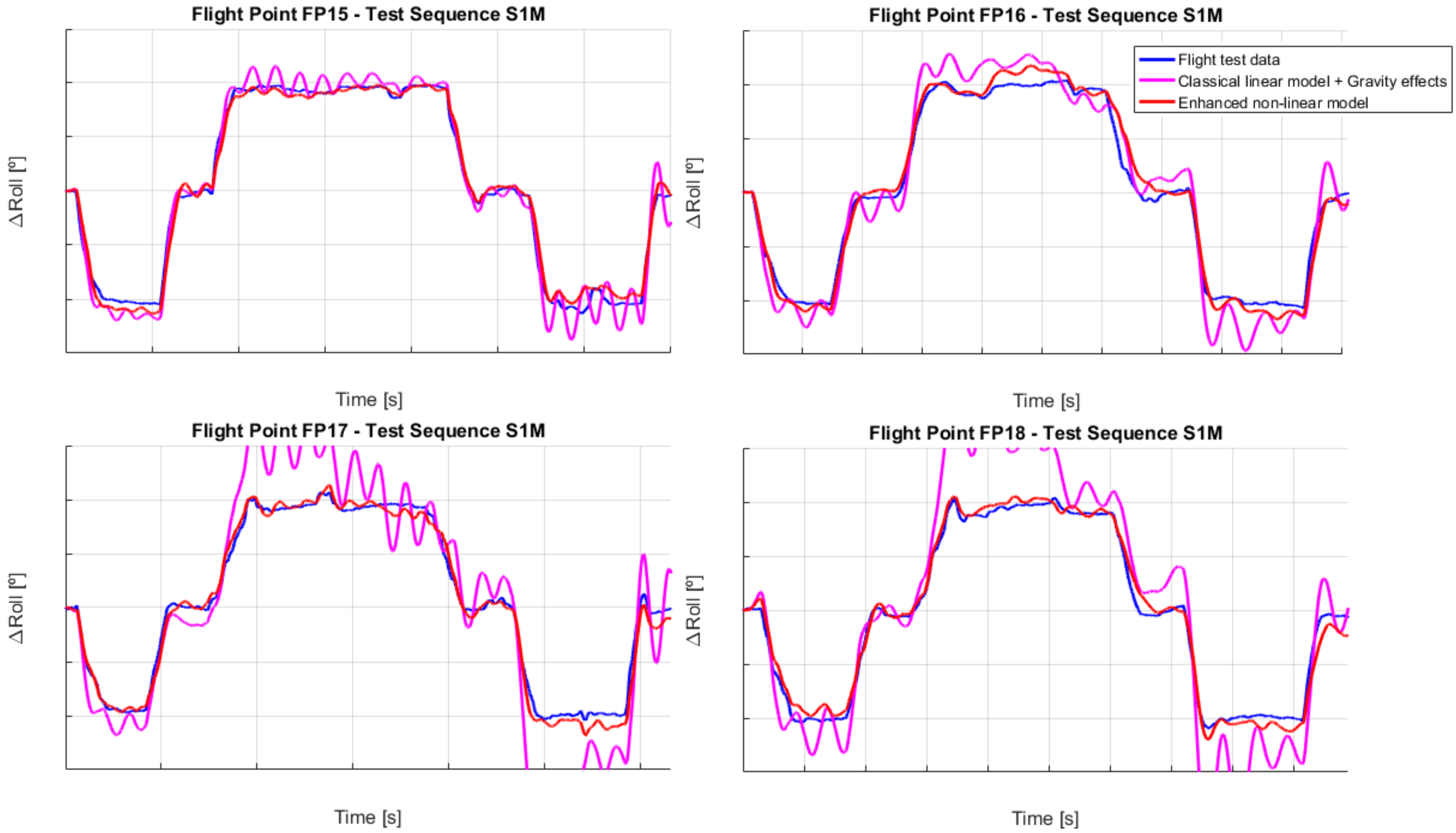


Figure 21 Boom roll angle evolution caused by quasi-steady antisymmetric deflections of the ruddervators. Flight test data (blue line) is compared with the following aeroelastic models: (a) Classical model including the gravity effects (magenta line) (b) Model including all the rest of effects (red line). It is seen the the final approach with all effects included (red line) is certainly closer to the flight test data (blue line).

6 CONCLUSIONS AND FURTHER ACTIVITIES

The AIRBUS Defence & Space Air-to-Air Refuelling Boom System is a mature product that is being extensively used by different Air Forces. Next step on this product has been to enhance the refuelling operation by including automated commanded-by-computer Boom motion in the closed-loop flight control laws. The closed-loop concept requires feedback from different positioning sensors and, for this purpose, the flexible deformation needs clearly be identified, i.e., the Aeroelasticity takes an important role. This paper has shown all the activities related to Structural Dynamic and Aeroelasticity that will make feasible the safe implementation of the automated refuelling.

The analyses have shown that classical methods used in the Aeroelastic domain are no longer valid for predicting accurate deformation of a kind of morphing geometry as the Boom, with large displacements and considerable changing shape while performing the operation. The aeroelastic model has been therefore complemented by adding different non-linear effects: gravity forces, flow detachment, incremental drag, variable geometry, configuration asymmetries, and additional damping measured in flight. Calculations have shown fairly good matching with flight test data, what confirms the enhanced non-linear aeroelastic model as adequate for supporting the Automated Air-to-Air Refuelling (A3R) Boom flight control laws design and for improving the Boom simulator by introducing more realistic elastic deformations.

Further activities will be focused on adapting this enhanced aeroelastic model to assess the requirements of the Flight Dynamics Team that is developing the A3R flight control laws.

The aeroelastic model should be ideally a black box running in real-time and delivering to the flight control laws the deltas on the sensors coming from the Boom flexible deformation.
Experience on the Boom system, a non-conventional structure, with large displacements and morphing structure/aerodynamics, has been a challenging work with acquired knowledge that will be for sure beneficial to other programs.
And … who knows the future of the AAR in the aviation. Imagine that in twenty years fuel resources are such that the AAR of airliners has become necessary. An study documented in [7] shows significant fuel savings on long range journeys by replacing the large long-range aircraft with short-range equivalents using AAR. For example, enabling 3000 nm range aircraft to complete long-range flights by AAR could provide fuel savings of 30-40% and financial benefits of 35-40%. And not only fuel consumption could be reduced: air pollution, maintenance and pilot training courses because of using a fleet of standard short-range aircrafts, etc. However, let's come back to ground, and think on the main identity of the civil aviation: safety. Standard civil regulations shall be reviewed (see for example [8]) and robust/fail-safe procedures shall be developed to fulfil the airworthiness requirements. The Automated Air-to-Air Refuelling A3R may certainly pave the road to this future.

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