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ADVANCED REFUELING BOOM SYSTEM (ARBS) DEVELOPMENT AND HANDLING QUALITIES EVALUATION

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Abstract

This paper describes the Advanced Refueling Boom System (ARBS) flight control system handling qualities development process. It also defines the key parameters for Flight Control Laws (FCL) design to achieve the required boom flying qualities and formulates the tasks required to assess the handling qualities of the ARBS.
Finally, this paper presents the results obtained during the flight test campaign conducted by Airbus Defence & Space (Military Aircraft) in order to qualify the handling qualities of the ARBS for the A330 Multi Role Tanker Transport (MRTT) program.

Nomenclature and abbreviations

AAR	Air To Air Refuelling
AEO	All Engines Operative
ALAS	Automatic Load Alleviation System
ARBS	Advanced Refuelling Boom System
ARO	Air Refuelling Operator
APC	Aircraft-Pilot Coupling
BAM	Bank Angle Mode
BEVS	Boom Enhanced Visual System
BCS	Boom Control System
BCU	Boom Control Unit
CAE	Contact Assessment Envelope
CHR	Cooper Harper Ratio
CL	Control Law
Elevation	Angle between the boom mast and the fuselage reference line of the tanker
ERS	Extension Retraction System
FBW	Flight By Wire
FCL	Flight Control Law
FCS	Flight Control Stick
FRU	Fuselage Refueling Unit
FT	Flight Test
FTT	Fine Target Tracking
HQ	Handling Qualities
MIL-STD	Military Standard
MRTT	Multi Role Tanker Transport
OEI	One Engine Inoperative
OFE	Operational Flight Envelope
PDL	Pilot Director Lights
PIO	Pilot Induced Oscillations
PIOR	Pilot Induced Oscillations Ratio
Pitch	Movement of the boom around pitch joint
RARO	Remote Air Refuelling Operator Console
Roll	Angle of rotation of the boom mast around the roll axis.
SSA	Safe Separation Assessment
TCS	Telescopic Control Stick
UAV	Unmanned Aerial Vehicle

1 Introduction

The Advanced Refuelling Boom System (ARBS) is currently the most advanced and sophisticated Fly-By-Wire (FBW) boom. It can be installed in the A330 Multi Role Tanker Transport (MRTT) allowing very fast fuel transfer rate. A330 MRTT is the ideal platform for tanker missions (as well as military transport aircraft). Its tank capacity is sufficient to supply the required fuel quantities without the need of any additional reservoirs or major structural modifications. A330 MRTT is the only new generation tanker-transport that is certified, in-service and combat-proven.

In the tanker version, the MRTT can be fitted with a combination of refuelling devices (underwing pods, fuselage refuelling unit (FRU) or FBW boom). It is capable of refuelling all receivers from Unmanned Aerial Vehicles (UAVs) and fighters to strategic bombers and large airlifters. All these refuelling capabilities, with the exception of UAVs, have already been successfully demonstrated during flight test.

A330 MRTTs have been ordered by 7 customers and it is now combat-proven by all those nations in which it is in-service (see boom operational contact with F15 in Figure [1-1])

Figure 1-1: A330 MRTT vs F15 pair to pair qualification

The Advanced Refueling Boom is fitted with a full digital FBW control system that provides the basic stability augmentation functions, transitions between different operational modes, transition to the reversion modes after failures and the desired handling qualities.

The capabilities of the Boom Control System (BCS) are very demanding and it is therefore required a well-defined and structured process to ensure that boom handling qualities requirements are fulfilled in the final qualification process with the customer.

Everything related to handling qualities is referred to the subjective appraisal of the operator to perform any intended task, and mainly to the effort that the operator has to apply to compensate the specific dynamic characteristics of the plant.

Aircraft development experience has shown that a flight control system development process based on pilots subjective evaluation in the simulator can lead to a non-adequate Flight Control Laws design when it is assessed in flight. On the other hand, flight control system development based on augmented system dynamic characteristics (flying qualities) is not a guaranty of success. Boom FCL development is based on a dual approach in which FCL design is based on:

- A set of target boom flying qualities criteria. Boom flying qualities are the open loop (aerial refueling operator is out of the control loop) boom augmented dynamic characteristics (aerodynamic plus boom dynamics plus BCS)
- A comprehensive set of test procedures for boom handling qualities assessment in simulation and in flight. Boom handling qualities are the properties of the boom plus Air Refuelling Operator (ARO) plus Boom Control System (BCS) evaluated in closed loop and it is influenced not only by boom flying qualities but also by additional factors such as side sticks characteristics, console ergonomic, Boom Enhanced Visual System (BEVS)

The experience gathered for aircraft handling qualities and the link of the dynamic characteristics to the level of the handling qualities provided by many users allows a sufficient correlation between pure physical plant characteristics and the resulting handling qualities level appreciated by the operators.

In the case of the tail boom, there is not available data that could help a new designer to link dynamic response characteristics to handling quality levels. Therefore it is necessary to define the key parameters used during FCL design and the subjective evaluation tasks to be performed during simulation and development flight test campaigns that ensure that ARBS flight control system meets the desired handling qualities criteria.

This paper defines the key parameters for FCL design to achieve the required boom flying qualities and formulates the tasks required to assess the handling qualities of the ARBS to ensure the fulfillment of the operational requirements in an Air to Air Refueling (AAR) mission.

These tasks and the corresponding handling qualities performance parameters presented in this paper are the result of a collaborative work among FCL design engineers, flight test engineers, experimental flight test pilots and experimental test ARO during the development process which has included hundreds of hours of flight testing and simulator testing.

Finally, this paper presents the results obtained during the Flight Test (FT) campaign conducted by Airbus Defence & Space (Military Aircrafts) in order to qualify the handling qualities of the ARBS for the A330 MRTT program.

2 ARBS Description

2.1 Configuration

The ARBS is basically made of a structural beam, two aerodynamic control surfaces, a telescopic inner tube and a hoist (see Figure [2.1-1]).

- The structural beam (boom mast) is attached to the tail cone of the tanker aircraft through a gimbal. This articulation allows movement of the boom in two axis: pitch and roll (see Figure [2.1-2]).
- The control surfaces, which will be referred to as ruddervators, are arranged in a V-tail configuration with 45º of dihedral. The deflection of the ruddervators goes from -60º to +20º.
- The telescopic inner tube is fitted with a nozzle and a coil at its aft end through a spherical articulation.
- The hoist is a cable that is attached to the boom mast and to the tanker tail cone and it is used during the deployment and the stowage of the boom.

2.2 System

There are 4 full-authority digital computers, which will be referred to as Boom Control Units (BCU), in a dual duplex configuration with two Control/Monitor groups.

The boom is controlled by the ARO from a Remote Air Refuelling Operator Console (RARO), which is situated in the cockpit of the tanker in order to facilitate the coordination of the Air-To-Air Refuelling (AAR) operation with crew cabin. The RARO is equipped with a TV 3D stereoscopic screen in which the boom position is displayed to the ARO through the BEVS. It is also displayed to the ARO information of boom pitch and roll position, telescopic length, FCL mode, disconnection envelope and warnings.

There is a hoist switch lever in the RARO with three positions (Raise, Hold and Lower) to command a boom deployment or stowage.

The boom attitude in pitch and roll is controlled by the ARO from the RARO through a FCS (Flight Control Stick), which is a side stick without any force feedback. The FCS position is transmitted to the BCU and it is translated into a boom attitude command through a command shaping function. The FCL algorithms use boom position and rate feedback to generate the control commands of the ruddervators so that the demanded position of the boom is achieved.

Centered FCS corresponds to boom trail position in which the ruddervators lift is nominally null, so that the pitching up moment due to the mast and telescopic drag is compensated by the pitching down moment of the boom weight.

The FCS includes a disconnect switch for normal disconnection (1st detent) and for independent disconnection (2nd detent).

The length of the telescopic tube is controlled by the ARO in free flight from the RARO through a Telescopic Control Stick (TCS). The TCS position is transmitted to the BCU and it is translated into a speed command to two external motors. A centered TCS is therefore corresponded with zero extension/retraction speed. In coupled flight the Extension Retraction System (ERS) is working in free-wheel mode so that the length of the telescopic is driven by the position of the receiver.

The TCS includes the following switches:

- An emergency contact switch to force the transition of the FCL to Coupled Mode
- A reset to ready button to force the transition of the FCL from Disconnected Flight Mode to Free Flight Mode.
- A directional pad for Pilot Director Lights (PDLs) control. The objective of the PDLs is to aid receiver positioning and its indications are manually controlled by the ARO during free flight and automatically generated by the BCU in coupled flight in order to position the receiver in the optimal contact position.

See ARBS BCS architecture in figure [2.2-1]

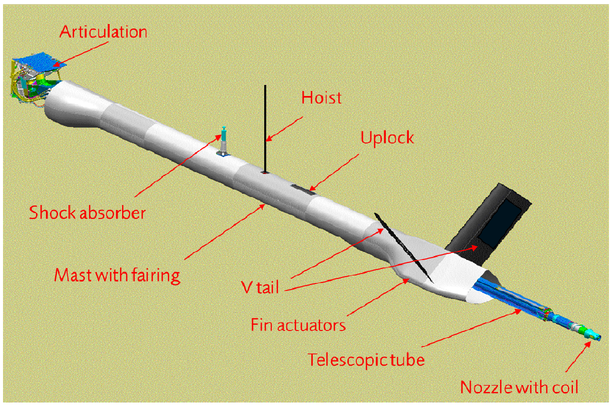


Figure 2.1-1: ARBS Lay-out

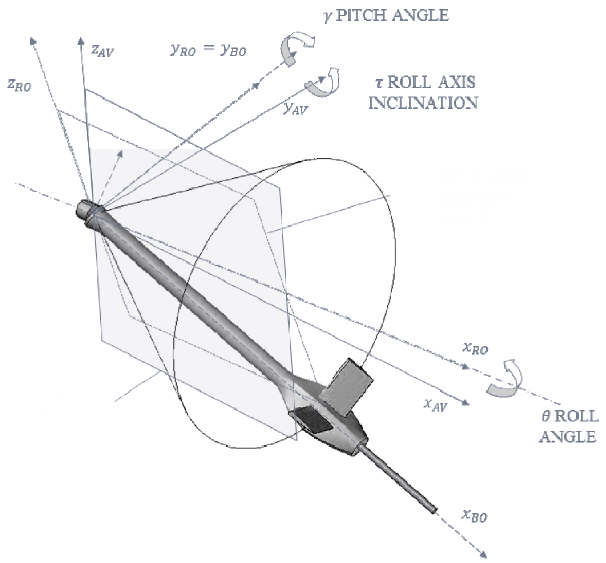


Figure 2.1-2: Boom axis scheme

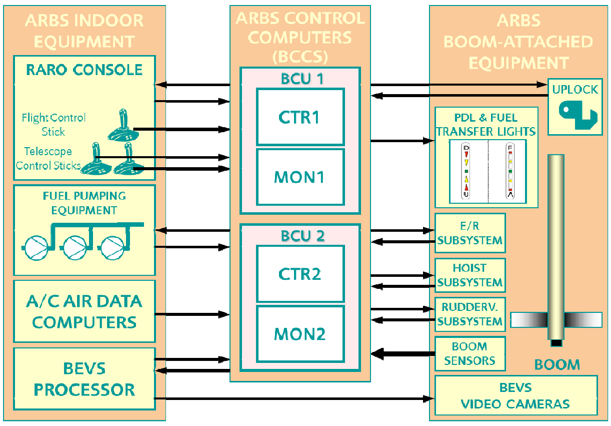


Figure 2.2-1: Top Level ARBS BCS Architecture

3 FCL Description

The FCL improve the natural stability of the boom (frequency and damping) and provide an adequate response to the ARO stick inputs (overshoot, rise time, time delay) in order to obtain a Level 1 of handling qualities for AAR Operation.

The design of the FCL is a challenge due to the following aerodynamic and structural characteristics that are inherent to the boom unaugmented plant.

- Very low rigid motion damping ratio.
- Different dynamic characteristics in pitch and roll axis that must be harmonized to obtained Level 1 of handling qualities.
- Variation of the rolling inertia with boom elevation due to the change of the rolling lever arm.
- Variation of drag and pitch inertia with telescopic extension or retraction.
- Variation of the boom inertia with the quantity of fuel in boom mast.
- Highly non-linear characteristics associated to a wide range of operation through the large elevation-roll spatial envelope and the flight operational envelope.
- Very low frequency of the structural modes in pitch and roll in free flight.
- Noticeable reduction of the structural frequencies and change of the mode shapes in coupled flight due to the modification of the physical constrains of the boom: from pinned-free in free flight to pinned-pinned during coupled flight.
- Variation of the structural frequencies with telescopic length and boom fuel content.

The high level of stabilization required together with a low frequency of the structural frequencies, makes structural coupling a real issue that must be addressed.

There is another challenge for the FCL designer due to the contradictory handling qualities requirements for each ARBS operation phase. While in free flight the boom must exhibit a good tracking response and fast control response, in coupled flight it should exhibit a neutral stability to minimize radial loads in the nozzle induced by the relative movement between tanker and receiver aircraft. Different control laws modes are therefore required for each ARBS operation phase. It must be also designed appropriate protection functions in each mode to cover the corresponding boom mode mismatch.

3.1 Hoisting: CL1

CL1 mode implements a control tension mode in pitch to maintain the tension of the cable within the operation band of the hoist system. It must be avoided an excessive download from the boom and also boom flotation.

In roll, CL1 mode implements an Integral, Derivative (ID) controller to maintain the boom within the plane of symmetry while at the same time provides adequate stability augmentation.

3.2 Free Flight: CL2 Small Receiver

It is used a Proportional, Integral, Differential (PID) controller with a Direct Link for the command path:

- The proportional and differential feedback improves the natural stability of the boom. A high level of augmentation is required due to the natural characteristics of the boom.
- The direct link improves the short term response of the boom to FCS inputs in terms of time delay and rise time.
- The integral path guarantees zero error between the attitude demanded with the FCS and boom position. Therefore, no trim devices or switches are required.

It is not possible to filter the first structural frequency with the classical notch filtering approach due to its proximity to the rigid mode frequency. It is therefore necessary to use a sensor data fusion technique described in Reference [1] to filter out the first flexible frequency without altering the feedback signal at the rigid mode frequency. The rest of structural modes frequencies are filtered with the classical notch filtering technique.

3.3 Free Flight: CL2 Large Receiver

Large receiver aircrafts sidewash change boom lateral stability characteristics, so that an adaptation of the FCL is needed.

CL2 Large Receiver mode implements the same pitch controller as CL2 Small Receiver.

A Proportional, Differential (PD) controller with a Direct Link for the command path is implemented in roll:

- The PD controller must provide adequate frequency and damping characteristics of the boom in close proximity with the receptacle in order to obtain good handling qualities during tracking. At the same time, a minimum damping of the boom in free-air shall be ensured. The design is a compromise between good handling qualities during tracking without penalizing the free-air response.
- The direct link gain is adjusted to obtain the same lateral envelope limits as in CL2 Small Receiver (with integral path) when the receiver is in close proximity.

3.4 Coupled Flight: CL3

During coupled flight, the boom movement is free without restrictions in both telescoping (extension or retraction) and boom attitude (pitch and roll). There is no flight task for the ARO other than monitoring nozzle loads. During this phase the FCS is moved by a Follow-Up motor to a position which corresponds to the free flight demand schedule.

In CL3 mode an Automatic Load Alleviation System (ALAS) is implemented. Its objective is to minimize radial loads in the boom nozzle to allow a smooth transition between coupled flight and disconnected flight without any transient in the boom. The ALAS function is attained through a Proportional, Integral (PI) controller in nozzle force and an inner proportional controller in boom attitude.

The notch filters are modified to take into account the reduction of the flexible frequency in coupled flight.

3.5 Disconnected Flight: CL2P Small / Large

The objective of this mode is to have a robust controller with enough flexible stability margins in cases of boom failure during disconnection (disconnect control laws mode but boom still coupled).

It is used a classical Proportional, Differential (PD) controller with a Direct Link for the command path:

- The proportional and differential feedback provides the same level of augmentation that in CL2 Small / Large.
- The direct link is adjusted to obtain nominally the same boom spatial envelopes as in CL2 Small / Large.
- The removal of the integral path provides a quicker response of the boom to obtain a safe clearance from the receiver during a separation manoeuvre.

It is used the same filtering technique for structural frequencies as in CL2 free flight.

3.6 ARBS flying qualities FCL design parameters

The definition of the key parameters for FCL design have been derived from the design used in air to air combat aircraft during precise attitude tracking tasks. Additionally, other robustness criteria are formulated from the same criteria required to aircraft flight control system.

- **Damping ratio**: All rigid modes must be well damped with a damping ratio target of 0.71.
- **Natural frequency**: A target of 3.1rd/s is set in order to obtain a quick response of the boom during tracking manoeuvres and during safe separation manoeuvres.
- **Harmonization of the temporal response in pitch and roll** (same dynamic in both axis)
- **High resistance to boom and operator dynamic coupling**: The guidelines are based on the specific requirements for Pilot Induced Oscillations (PIO) in the frequency domain which were formulated by Gibson (see Reference [2]) in order to guarantee a high degree of PIO resistance. The PIO resistance parameters are formulated in the boom attitude to stick input frequency response. The following values must be taken as a guideline since a non-compliance in one of this parameters only indicates an area prone to PIO, which must be confirmed through a close-loop test evaluation in the simulator or in-flight.
  - Frequency at 180º phase lag: higher than 0.8 Hz.
  - Phase rate at 180º phase lag: not higher than 70º/Hz
  - Amplitude at 180º phase lag: 10dB below the amplitude at 110º phase lag, which is considered representative of the crossover frequency.
- **Control robustness**: The level of stabilization achieved through FCL feedback must not lead to unstable situations. The requirements are based on military standard (MIL-STD) specifications (see Reference [3]) and are formulated in terms of open loop stability margin of the control system:
  - Rigid modes: 6dB of gain margin and 45º of phase margin regardless of the speed or frequency of the mode.
  - Structural modes: 9 dB of gain margin being amplitude stabilized and not allowing phase stabilization so that this gain margin must be kept at all flexible frequencies regardless of the phase lag.

4 Test procedures for handling assessment

The tests procedures defined for ARBS handling qualities assessment will demonstrate both certification and qualification requirements and will be the basis for the subjective evaluation of the boom handling qualities during the ARBS development process.

A set of evaluation tasks and required handling qualities Levels for the different ARBS operational phases have been defined to demonstrate basic AGARD 300 Vol-11 recommendations (Reference [4]): *“the AAR equipment must be shown to be capable of dispensing fuel reliably within the declared dispensing envelope. No undue skills should be demanded of the tanker aircrew”.*

4.1 ARBS Handling Qualities during hoisting

4.1.1 Test Objective

Demonstrate adequate boom handling qualities during the hoisting phase (lowering and raising) within the AAR Tanker Operational Flight Envelope (OFE).

ARBS hoisting phase is defined as a hands-off operation being ARO task to monitor the correct boom behavior during the hoisting phase.

4.1.2 Hoist evaluation criteria

The acceptance criteria shall be:

- ARBS hoisting flight control laws mode shall provide boom lowering and raising capability (from stowed to trail position and from trail up to stowed position) within the full operational envelope without the need of ARO intervention except to monitor that boom is nominally within the aircraft plane of symmetry during the hoisting phase.

4.1.3 Test Procedure

1. Deploy the boom down to trail in steady straight and level flight.
2. Raise the boom to stowed position in steady straight and flight.
3. Deploy the boom to trail while the aircraft is manoeuvring in Bank Angle Mode (BAM) (or manually) up to 30º bank angle.
4. Raise the boom to stowed position while the aircraft is manoeuvring in BAM (or manually) up to 30º bank angle.

4.2 ARBS Handling Qualities in free air

ARBS free air handling qualities assessment will be performed by means of the Contact Assessment Envelope (CAE) manoeuvre and the Safe Separation Assessment (SSA) manoeuvre. CAE will be performed with CL2 FCL in two steps:

- CAE 1: Azimuth and elevation captures.
- CAE 2: Evaluation of maximum spatial envelope authority limits

SSA will be performed with disconnect FCL modes:

- SSA: Evaluation of CL2p FCL handling qualities characteristics during large emergency separation type manoeuvres

4.2.1 Contact Assessment envelope

4.2.1.1 CAE1 (attitude captures) task

The task of the ARO is as follows:

1. Starting from the boom initial position, move the boom at an operationally representative boom rate through the control envelope to capture the positions defined in table 4.2.1.1-1 and using a predefined set of CAE 1 Task Tolerances (see below).
2. Return Cooper Harper Ratio (CHR) (see Appendix A-1) and Pilot Induced Oscillations Ratio PIOR (see Appendix A-2) values (see References [5] & [6]) and comments for the stick movements and ARO compensation to capture each position and maintain this position. Qualitatively assess boom controllability between capture points.
3. In order to demonstrate a level of PIO robustness, the ARO may repeat step (1) using more aggressive inputs with

operationally representative boom rates and tighter capture tolerances attempting to avoid all overshoot or capture error. Assign PIO tendency ratings (PIOR) accordingly with rating scales defined at Appendix A-2 and add comments about the stick movements and ARO compensation to capture each position and maintain this position

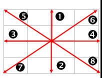
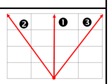
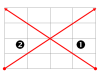
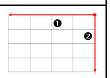
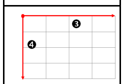
4. Repeat (1), (2) and (3) at different telescopic tube lengths from full extended to full retract.

CAE1: Tolerances & evaluation criteria

Boom response to ARO stick input shall be prompt and possess suitable dynamic characteristics to allow smooth, predictable and accurate capture and maintenance of attitude positions throughout the envelope

- **Desired**: Capture and maintenance of required attitude within ± 2° roll and elevation.
- **Adequate**: Capture and maintenance of required attitude within ± 3° roll and elevation.

Table 4.2.1.1-1 CAE1 manoeuvre

DEFINITION OF CONTROL ENVELOPE ASSESSMENT (CAE-1)		
ACTION	DESCRIPTION	
1	From TRAIL position perform the following attitude captures: 1. Min elevation, zero roll (back stick) 2. Max elevation, zero roll (forward stick) 3. Max left roll at trail elevation (left stick) 4. Max right roll at trail elevation (right stick) 5. Max left and upper corner (diagonal stick) 6. Max right and upper corner (diagonal stick) 7. Max left and lower corner (diagonal stick) 8. Max right and lower corner (diagonal stick	
2	From the MAX elevation (0º roll) achieve the following MINIMUM attitude captures	
3	From maximum LOWEST (right then left) corner achieve the maximum UPPER opposite corners	
4	From maximum UPPER (right then left) corner perform the following attitude captures	 

4.2.1.2 CAE2 (limit envelope assessment) task

Manoeuvre the boom in the extreme elevation spatial areas where the maximum attainable roll angle is a function of the boom elevation. Subjectively evaluate boom predictability close to authority boundary limits. See CAE-2 manoeuvre definition details at table 4.2.1.2-1 and 4.2.1.2-2

CAE2 Evaluation criteria

The boom response to stick inputs will be progressive and predictable throughout the control envelope. Check the adequacy of the boom response characteristics when the limits of the envelope are reached

Qualitatively evaluate boom control and predictability during boom attitude captures at control authority limits using operational boom stick inputs.

Questionnaire for the boomer:

Is there any noticeable un-commanded movement when the stick gets into the dead zone area?	YES	NO
If un-commanded movement is noticed, can it be easily compensated?	YES	NO

Table 4.2.1.2-1 CAE2 authority limits

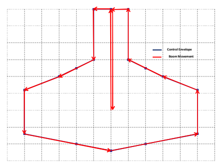
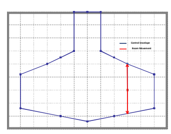
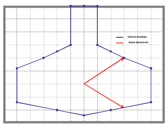
DEFINITION OF AUTHORITY LIMITS ENVELOPE ASSESSMENT (CAE-2)	
ACTION	DESCRIPTION
1) Starting from TRAIL position 2) Slowly (~1º/sec) pull back to lowest elevation for the corresponding flight condition (0º roll) 3) Fly the boom around the boundary control envelope maintaining the FCS max deflected 4) Return to TRAIL (FCS centered)	

Table 4.2.1.2-2 CAE2 predictability

BOOM PREDICTABILITY CLOSE TO MAXIMUM AUTHORITY LIMITS	
ACTION	DESCRIPTION
1) Starting from TRAIL and 50% of maximum roll 2) Apply pure pitch up input at representative boom rate (from 2 to 6 deg/sec) up to the min pitch authority limit at 50% of maximum roll for the corresponding flight condition 3) Back to TRAIL and 50% of maximum roll 4) Apply pure pitch down input at representative boom rate (from 2 to 6 deg/sec) up to the max pitch authority limit at 50% of maximum roll for the corresponding flight condition 5) Back to TRAIL	

BOOM PREDICTABILITY CLOSE TO MAXIMUM AUTHORITY LIMITS	
ACTION	**DESCRIPTION**
1) Starting from TRAIL position 2) Apply diagonal stick input at representative boom rate (from 2 to 6 deg/sec) up to 50% of maximum roll and min authority in elevation 3) Back to TRAIL 4) Apply diagonal stick input at representative boom rate (from 2 to 6 deg/sec) up to 50% of maximum roll and max authority in elevation 5) Back to TRAIL *<u>Note</u>: Perform right and left captures alternative for each test condition*	

4.2.2 Safe Separation Assessment (SSA)

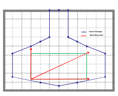
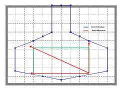
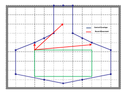
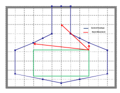
The objective of safe separation assessment in free air is to assess disconnect flight control laws handling qualities characteristics during large emergency separation type manoeuvres. The ARO evaluates boom response in disconnect mode while controlling safe boom separation (maintain a safe position from receiver). See SAA definition at table 4.2.2-1.

<u>SSA Evaluation criteria</u>

Evaluation criteria based on the capability to establish and maintain a safe clearance between boom and receiver aircraft:

- **Desired**: After disconnect, the boom should be controllable and predictable without intrusive dynamics or PIO effect. Safe separation, capture and maintenance of a safe position with minimal operator corrections or effort.
- **Adequate**: After disconnect, the boom should be controllable and predictable without intrusive dynamics or PIO effect. Safe separation, capture and maintenance of a safe position without continuous operator corrections or effort.

<u>Table 4.2.2-1 SSA task procedure</u>

DEFINITION OF CONTROL SAFE SEPARATION ASSESSMENT (SSA)	
ACTION	**DESCRIPTION**
From LOWER LEFT position of disconnect envelope perform the following captures and maintain a safe position 1) Upper Left (pure pitch input) 2) Lower Right (pure roll input) 3) Upper Right (diagonal)	
From LOWER RIGHT position of disconnect envelope perform the following captures and maintain a safe position 4) Upper Right (pure pitch input) 5) Lower Left (pure roll input) 6) Upper Left (diagonal)	
From UPPER LEFT position of disconnect envelope perform the following captures and maintain a safe position 7) Upper Right (pure roll input) 8) Upper Right (slight pitch-up input plus roll input) 9) Stovepipe area (very low elevation in the plane of symmetry)	
From UPPER RIGHT position of disconnect envelope perform the following captures and maintain a safe position 10) Upper Left (pure roll input) 11) Upper Left (slight pitch-up input plus roll input) 12) Stovepipe area (very low elevation in the plane of symmetry)	

4.3 ARBS Handling during AAR operation

4.3.1 Test Objective

The test objectives are to demonstrate adequate ARBS handling qualities for the coupling, fuel transfer and disconnection phases within the Refuelling Tanker OFE.

During the receiver approach to contact position, boom handling shall be suitable to accurately keep the boom in the trail position to indicate to the approaching receiver aircraft the intended contact position and to precisely move the boom during the final approach to allow the receiver to reach the contact position (boom movement is required to avoid the canopy of some receivers).

Related to easiness of coupling capability, the main evaluation will be based in CHR during fine tracking of the receiver aircraft receptacle and coupling.

To explore handling qualities in operational conditions, contacts will be performed first around trail positions and then expanded to the corners of the contact envelope.

In order to homogenize assigned contact coupling ratings, ARO shall provide also a subjective indicator to compare receiver aircraft stabilization when compared with typical operational conditions. This indicator will be referred to as receiver a/c stabilization index.

Once coupled, ALAS operation shall be reliable during the fuel transfer phase while the receiver aircraft is kept within the disconnect envelope. As ARBS coupled flight control laws do not required ARO workload in terms of boom controllability, evaluation will be based on the adequacy of the ARBS ALAS function to perform the intended task.

Finally, boom handling qualities shall be adequate to guarantee safe aircraft separation after AAR disconnection, either automatically performed by the ARBS or manually commanded by the ARO or the receiver pilot, at the end of fuel transfer or as a consequence of high nozzle loads or the boom reaching the disconnection limits. The evaluation shall ensure adequate capability to perform large amplitude receiver aircraft avoidance maneuvers. The evaluation will be based on CHR assignment.

During transition from CL2p to CL2 through Reset to Ready button, qualitatively evaluate boom and stick response with hands off the stick and also evaluate the response while attempting to maintain boom position.

4.3.2 AAR Operation Evaluation criteria

1. Boom Control: Evaluate boom handling, through ARO inputs and boom response to maintain the boom in trail and to manoeuvre the boom allowing receiver a/c reaching the final contact position. Evaluation criteria based on ARO subjective comments regarding capability to perform the task and the required ARO compensation.
    - **Desired**: boom movement should be controllable and predictable without intrusive dynamics or PIO effect. Boom control shall be performed with minimal operator corrections or effort.
    - **Adequate**: boom movement should be controllable and predictable without intrusive dynamics or PIO effect. Boom control shall be performed without continuous operator corrections or effort.
2. *Fine Target Tracking (FTT):* Evaluate boom handling, through ARO inputs (control forces, displacements and effort) and boom response to track the receiver's receptacle with the boom nozzle.

    The assessment will be based on the ARO capability to follow the receiver movements in the contact envelope waiting for the receiver stabilization and the accurate tracking capability to achieve a precision contact when the receiver is already stabilized around the target control envelope corners.

    Tracking capability will be based on deviations in terms of boom nozzle and target contact position. Boom response to ARO stick inputs shall be prompt and possess suitable dynamic characteristics to allow smooth, predictable and accurate tracking of the receptacle to achieve a precision contact. CHR evaluation thresholds are:
    - **Desired**: keeping the boom nozzle aligned within one nozzle diameter around the receptacle centre.
    - **Adequate**: based on keeping the boom nozzle over the slipway of the receptacle, as this will allow a successful contact.
3. *Contact Coupling:* Evaluate boom handling, through ARO inputs (control forces, displacements and effort) and boom response while performing coupling.

    Capability to perform the coupling will be based on the capability to perform precision contacts. CHR evaluation thresholds are:
    - ***Desired***: Achieve a precision contact coupling meaning that it is not a slipway assisted contact.
    - ***Adequate:*** Achieve coupling allowing acceptable nozzle contact on UARRSI's slipway "slipway assisted contact".
4. ALAS Performance The acceptance criteria shall be:
    - ARBS coupled flight control laws mode shall provide automatic loads alleviation within the disconnect envelope within the full operational envelope without the need of ARO intervention.

- Check the adequacy of the stick shaker function to prevent inadvertent ARO stick inputs while in coupled flight.

5. _Safe Separation Assessment:_ Evaluate boom handling through ARO inputs (control forces, displacements and effort) and boom response, while performing a safe boom separation from receiver in ARBS disconnection mode. Evaluation criteria based on the capability to establish and maintain a safe clearance between boom and receiver aircraft.
   - **Desired**: After disconnect, the boom should be controllable and predictable without intrusive dynamics or PIO effect. Capture and maintenance of a safe position with minimal operator corrections or effort.
   - **Adequate**: After disconnect, the boom should be controllable and predictable without intrusive dynamics or PIO effect. Capture and maintenance of a safe position without continuous operator corrections or effort.

4.3.3 Test Procedure

1. A330-MRTT deploys boom to nominal trail position. The receiver is in pre-contact position (~ 25ft astern of the boom nozzle).
2. _Boom Control_: The receiver moves to the contact envelope using typical closure rate between 1 and 2 fps.

   The ARO maintains boom position to indicate approaching receiver aircraft the intended contact position and manoeuvres (if required) the boom to allow receiver a/c reaching the final contact position.
3. _Fine Target Tracking (FTT):_ ARO tracks the receiver's receptacle with the boom nozzle trying to minimize the boom nozzle and target centre receptacle misalignment.

   Tracking task will be performed in trail position as representative of the optimum contact envelope conditions and then when the receiver is stabilized around the control envelope corners.

   Evaluation criteria shall be assessed during a limited period of time operationally representative of the fine target tracking task (ten seconds is considered operationally representative) while the receiver tries to keep the target contact envelope corners

   Tracking task evaluation will be performed at different telescopic tube lengths.
4. _Contact Coupling:_ Contacts will be performed first around trail positions and then expanded to the corners of the contact envelope.

   The task for the receiver pilot is to stabilize the aircraft in the selected position to perform the contact.

   The ARO performs coupling while the receiver aircraft is kept within the contact envelope limits:
   - During straight and level flight.
   - Up to 30 degrees banked turns.
5. _ALAS Performance:_ The receiver manoeuvres behind the A330-MRTT in straight and level flight within the disconnection flight envelope.

   ARO monitors ALAS functionality and check the adequacy of the stick shaker function to prevent inadvertent ARO stick inputs while in coupled flight.

   A330-MRTT rolls into a turn of up to 30º bank under either manual or autopilot control and then reverses the turn while the receiver follows, keeping within the contact envelope, and then levels off.
6. _Safe Separation Assessment:_ ARO performs a normal disconnection from disconnection envelope corners

   ARO flies the boom to a safe position from receiver until the receiver aircraft leaves the contact position and evaluate boom handling while controlling safe boom separation.

   During reset to ready after disconnect, qualitatively evaluate boom and stick response with hands off the stick and while trying to maintain boom steady

5 ARBS Handling Qualities Test Results

The initial handling qualities qualification exercise of the ARBS identified a number of deficiencies.

As a consequence of the ARBS handling qualities non-compliances identified during the initial qualification campaign, an enhancement of the ARBS FCL (upgrade III) was developed.

The results from the ARBS handling qualities qualification process performed with the upgrade III FCL was fully satisfactory. Handling Qualities assessment was performed by three different AROs and the Cooper Harper and PIO ratings provided are fully consistent between them.

During the qualification program, two types of receivers were utilized (Australian A330 MRTT-KC-30A and Portuguese Air Force F-16A/B) as representative of a wide body large receiver and a fast jet receiver respectively.

5.1 Hoisting capability assessment

Hoisting operation (lowering and raising while the tanker is in straight and level flight and while the aircraft is maneuvering in a banked turn) was assessed with tanker aircraft All Engines Operative (AEO) and in One Engine Inoperative (OEI) conditions along the refueling envelope.

It was demonstrated that hoisting flight control laws are adequate to perform the task without the need of ARO intervention except monitoring the boom lowering or raising.

5.2 ARBS Handling Qualities in free air

CAE1, CAE2 and SSA manoeuvres in free air with small and large receiver flight control laws were assessed for three different telescopic tube lengths (6ft, 12ft and 21ft), with tanker aircraft AEO and OEI conditions and along the refueling envelope.

CAE1 test results show that boom CL2 FCL provides homogenous boom handling qualities in the operational envelope compensating AEO or OEI operation, small or large receiver FCL modes or telescopic length effects, (see Figures 5.2-1, 5.2-2 and 5.2-3). Results show that boom handling qualities are Level 1 (CHR 3 or better) and boom dynamics is free of PIO tendency (PIOR 2 or better).

CAE2 test results shows that boom response to stick input is progressive and predictable throughout the control envelope without noticeable un-commanded movements during the boundary captures and when some un-commanded movement is notice by the ARO it is easily compensated. Figure 5.2-4 shows a summary of the predictability test results (diagonal and vertical captures).

Large emergency separation type manoeuvres (SSA) with disconnect control laws met desired performance. After disconnect, the boom is controllable and predictable without intrusive dynamics or PIO effect. No differences in the boom performance was noted during SSA manoeuvre regardless of the combination of boom probe lengths, disconnect position (elevation and roll) or flight condition

It can be concluded that free air results have demonstrated that boom is controllable, predictable and free of any APC/PIO tendency throughout the boom operational envelope (both tanker flight envelope and boom spatial envelope).

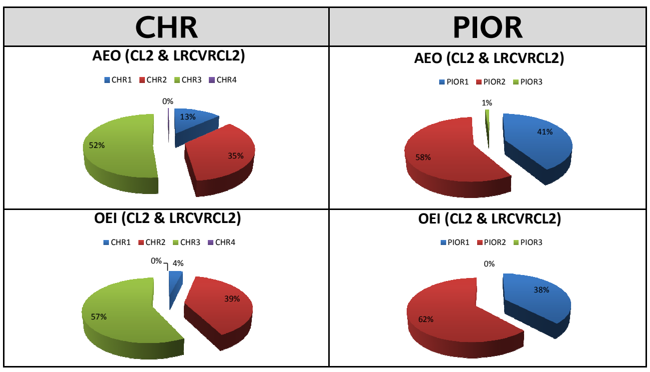


Figure 5.2-1: CAE1 CHR & PIOR (AEO and OEI)

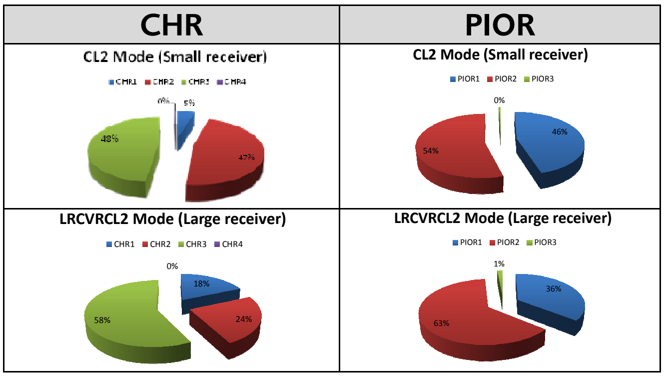


Figure 5.2-2: CAE1 CHR & PIOR (small & large)

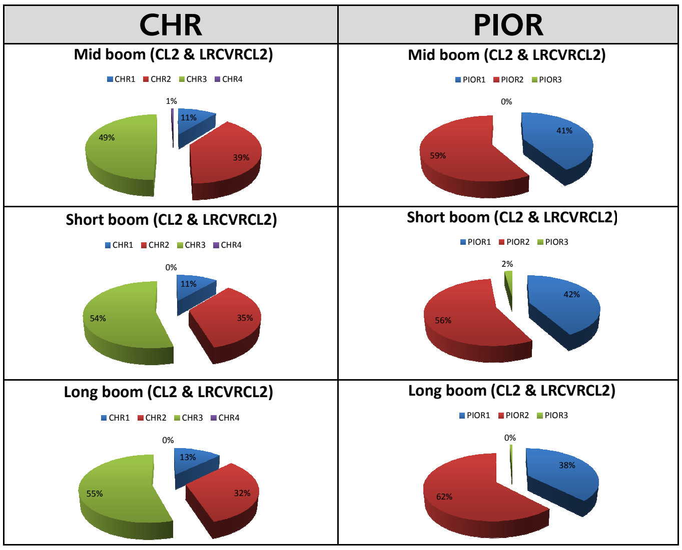


Figure 5.2-3: CAE1 CHR & PIOR (telescopic effect)

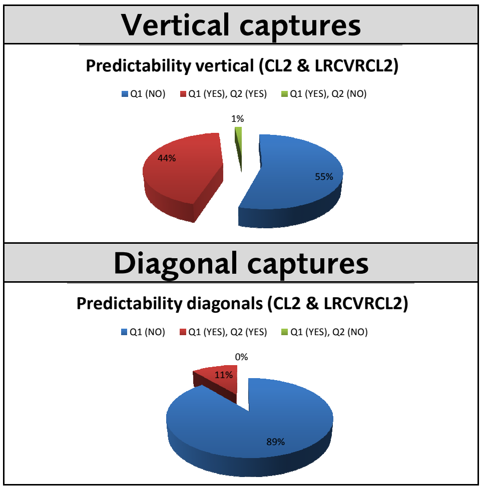


Figure 5.2-4: CAE2 Predictability questionnaire result (See CAE2 evaluation criteria)

5.3 ARBS Handling during AAR operation

The objective is to perform contacts & disconnections in the corners and in the middle of the contact/disconnection envelope, with different probe lengths (short, mid, long) and with small (F16B) and large (KC-30) receivers.

Cooper Harper and PIO ratings provided by different AROs are fully consistent.

Test results shows that boom control laws provides homogenous boom handling qualities in the operational envelope compensating telescopic length effects, AEO and OEI operation and there are not noticeable differences in boom handling with small or large receiver control laws mode. Figures 5.3-1 and 5.3-2 present ARO ratings (CHR and PIOR) during F16 and A330 MRTT receiver's receptacle tracking task (data provided in the optimum contact envelope and in the full contact envelope) and figure 5.3-3 present ARO ratings during F16 and A330 MRTT contact coupling task.

After disconnection, the boom is controllable and predictable without intrusive dynamics or PIO effect. Safe separation from receiver aircraft in terms of capture and maintenance of a safe position was possible with minimal operator corrections or effort.

ALAS minimizes nozzle loads within the disconnect envelope during fuel transfer in straight and level and during turns up to 30º bank without the need of ARO intervention.

Stick shaker function avoid inadvertent ARO stick inputs while in coupled flight and it is not intrusive during contact coupled phase allowing ARO to guard the stick without stick shaker interference.

It can be concluded that satisfactory boom contact and safe separation capability have been demonstrated throughout the AAR tanker Operational Flight Envelope (aircraft mass, speed and altitude) with small and large receiver. The boom is fully controllable and predictable, free of any APC/PIO tendency and provides adequate handling qualities (Level 1 within the optimum contact envelope and Level 1/2 within the full contact envelope) for the contact coupling task.

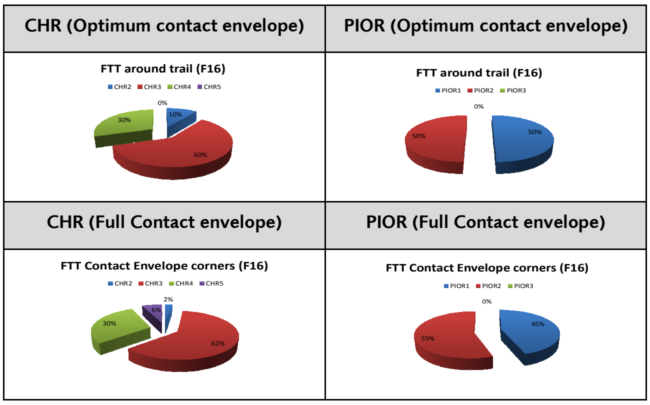


Figure 5.3-1: Receptacle fine target tracking (F16)

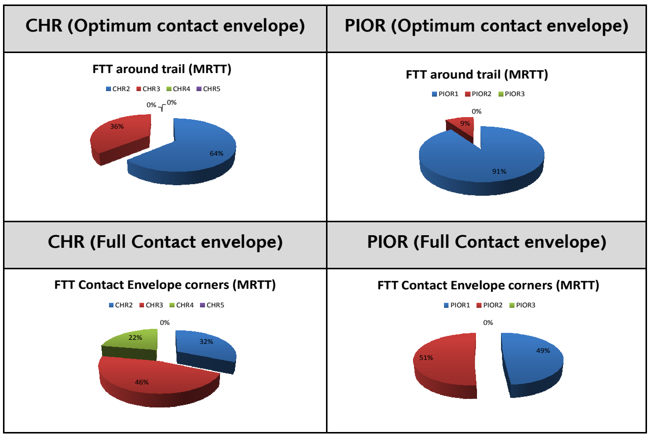


Figure 5.3-2: Receptacle fine target tracking (MRTT)

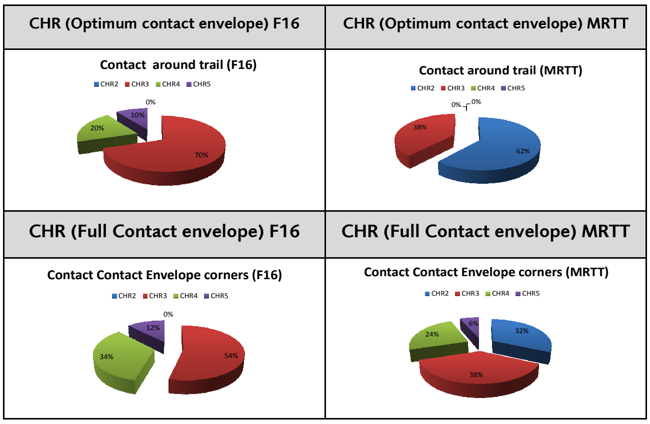


Figure 5.3-3: AAR Contact Coupling (F16 & MRTT)

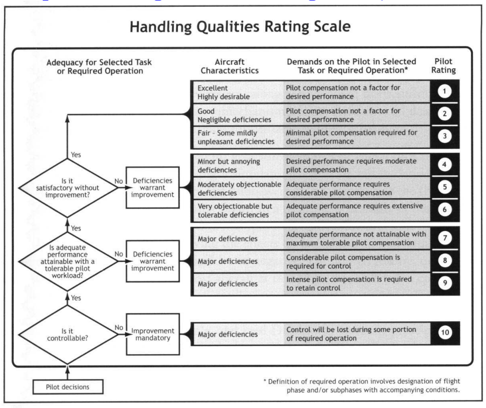
6 Conclusions

Experiences gained with handling qualities testing for ARBS show that successful handling qualities testing can only be performed if it is followed a well-defined process. This process shall involve from the very beginning major stakeholders and shall promote a collaborative work among FCL design engineers, flight test engineers, experimental flight test pilots and experimental test ARO. Considering the inherent subjective nature of the handling qualities evaluation, involvement of the customer handling qualities qualification operator during system development process is a guarantee of success.

7 Appendixes

7.1 Appendix A-1

Cooper Harper Handling Qualities Rating Scale (NASA TN D-5153)



7.2 Appendix A-2

PIO Tendency Rating Scale (MIL-HDBK-1797)

DESCRIPTION	NUMERICAL RATING
No tendency for pilot to induce undesirable motions.	1
Undesirable motions tend to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique.	2
Undesirable motions easily induced when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated but only at sacrifice to task performance or through considerable pilot attention and effort.	3
Oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.	4
Divergent oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must open loop by releasing or freezing the stick.	5
Disturbance or normal pilot control may cause divergent oscillation. Pilot must open control loop by releasing or freezing the stick.	6

8 References

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