Air-to-Air refuelling fidelity for training outcomes on the Wedgetail Operational Flight Trainer

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ABSTRACT

Accepted into service in 2007, the Wedgetail Operational Flight Trainer (OFT) is a level D equivalent accredited, simulator qualified under International Civil Aviation Organisation (ICAO) Manual of Criteria for the Qualification of Flight Simulators (MCQFS) Level II 1st edition, situated at Williamtown, NSW. The OFT provides Royal Australian Air Force (RAAF) pilots with Zero Flight Time training on the E-7A AEW&C Wedgetail platform. A component of this training is Air-to-Air Refuelling (AAR) which has partial training credits authorised under a credit sequence.

Until recently, the majority of the AAR Training in the OFT was focused on the approach to and initial contact with the Tanker. This was achieved by modelling the tanker wake field in the OFT and incorporating this flow field into the aerodynamics experienced by the Ownship. This provided a high fidelity representation of the approach experienced by the Wedgetail when flying to make initial contact with the Tanker boom.

With the Wedgetail AEW&C achieving Final Operational Capability in 2015, aircrews have been logging more AAR time. As a result, differences were identified by Pilots in the longitudinal stability response of the OFT with respect to the tanker when in a connected tanking state. This difference was a result of Tanker Boom and Ownship force and moment interactions not being modelled. These interactions provide significant feedback on the Ownship, improving stability when connected to the Tanker.

This paper reviews the AAR modelling concept in the Wedgetail OFT and discusses the approach Thales Australia took to improve the AAR Fidelity with respect to tanking in a connected state with the flying boom.

1 INTRODUCTION

Air-to-Air refuelling (AAR) provides air assets long endurance, delivering the extended flight time and range to complete missions that would otherwise not be possible. The Royal Australian Air Force’s (RAAF’s) E-7A AEW&C Wedgetail provides airborne early warning and threat detection, along with command and control of the tactical battle space. Given the E-7A’s critical role in commanding the battlespace and coordinating military assets, keeping the E-7A airborne for extended periods of time is essential. AAR provides this staying power.

However, AAR presents a risk of an air collision, due to the need to maintain close proximity flying during tanking, and the need to fly into and continually fight the aerodynamic wake of the Tanker (Landry, P.F. 1997). Noting the importance of AAR for mission effectiveness of the E-7A AEW&C platform, having pilots trained and qualified to perform such manoeuvres is critical to ensuring continued operational capability.

To facilitate safe and cost effective training of E-7A pilots in AAR, the Wedgetail Operational Flight Trainer (OFT) provides a high fidelity AAR training capability. The Wedgetail Operational Flight Trainer (OFT) is a level D equivalent accredited simulator qualified under International Civil Aviation Organisation (ICAO) Manual of Criteria for the Qualification of Flight Simulators (MCQFS) Level II situated at Williamtown, NSW. The OFT provides RAAF pilots with Zero Flight Time training on the E-7A AEW&C Wedgetail platform, along with partial training credits for AAR authorised under a credit sequence.

Since being accepted in 2007, the majority of AAR training in the OFT was focused on the approach to and initial contact with the Tanker. The OFT AAR training capabilities have been widely regarded as being extremely important, from both a safety and aircraft usage cost reduction aspect, in training pilots on how to conduct this manoeuvre. However, with the E-7A Wedgetail achieving Final operational Capability in 2015 and being deployed on Operation OKRA, aircrews have been logging more AAR time. As a result, pilots have noted differences in the longitudinal stability response of the Ownship when in close proximity to the Tanker compared with the actual aircraft. To address this fidelity gap, an update to the OFT AAR model was required.

High fidelity simulations of AAR have been developed previously for analysis (Smith, J.J., 2007), and to enable computer control of AAR itself (Thomas, P.R. et al. 2015). However, to achieve the required AAR training outcomes a different level of fidelity was needed. The key requirement is to ensure the OFT model is accurate for pilot training outcomes. Ideally, a detailed dynamic model would be developed, based on model parameters extracted from a significant amount of flight test data. However, this approach is expensive and time consuming. Alternatively, given we have control over the simulation environment and absolute knowledge about both the Tanker and Ownship, it is possible to make concessions in the model fidelity. Instead constructing a first principles model using a dynamics based approach, then in place of a data set we use subjective tuning to achieve the desired training outcomes.

This paper is in six sections. Section 1 is this introduction. Section 2 details the notation used in this paper. Section 3.1 details the Wedgetail Air-to-Air Refuelling model, prior to the fidelity enhancement discussed in this paper. Section 3.2 details the longitudinal stability issue experienced by the pilots and the analysis which identified the root cause with the model fidelity. Section 3.3 details the fidelity enhancement made to the Wedgetail AAR model. Section 3.4 details the approach for subjective tuning the AAR model enhancement. Section 4 provides concluding remarks and a summary on the enhancements made to the AAR model. Section 5 is acknowledgements for those who assisted with the development of this body of work. Section 6 lists the citations referenced in this paper.

2 NOTATION

The nomenclature used in this paper is given in Table 1.

Table 1: Nomenclature

Symbol	Description
$\{F\}$	Forces acting on Ownship
$\{F_{\text{aero}}\}$	Forces acting on Ownship as a result of the aerodynamics
$\{F_{\text{eng}}\}$	Forces acting on Ownship as a result of the engine thrust
$\{F_{\text{gnd}}\}$	Forces acting on Ownship as a result of the ground effects
$\{F_{\text{boom}}\}$	Forces acting on Ownship as a result of the Tanker Flying Boom interaction
$[\mathrm{m}]$	Ownship mass
$\{\mathrm{a}\}$	Ownship acceleration
$\{M\}$	Moments acting on Ownship around its Centre of Mass
$\{M_{\text{aero}}\}$	Moments acting on Ownship about its Centre of Mass as a result of the aerodynamics
$\{M_{\text{eng}}\}$	Moments acting on Ownship about its Centre of Mass as a result of the engine thrust
$\{M_{\text{gnd}}\}$	Moments acting on Ownship about its Centre of Mass as a result of the ground effects
$\{M_{\text{boom}}\}$	Moment acting on Ownship about its Centre of Mass as a result of the Tanker Flying Boom interaction
$[\mathrm{I}]$	Ownship Inertia Tensor
$\{\alpha\}$	Ownship angular acceleration
$\{\omega\}$	Ownship angular velocity
θ	Flying Boom pitch angle from nominal centre
ψ	Flying Boom yaw angle from nominal centre
x	Flying Boom retraction length from full extension
τ_θ	Pitch Moment about Flying Boom pivot
τ_ψ	Yaw Moment about Flying Boom pivot
F_{TR}	Force acting in x direction in $\{\mathrm{TR}\}$ reference frame
d_{b}	Length of Flying Boom
$\mathrm{K}_{\mathrm{r}\theta}$	Spring constant acting on Flying Boom in pitch
$\mathrm{B}_{\mathrm{r}\theta}$	Damping constant acting on Flying Boom in pitch
$\mathrm{K}_{\mathrm{r}\psi}$	Spring constant acting on Flying Boom in yaw
$\mathrm{B}_{\mathrm{r}\psi}$	Damping constant acting on Flying Boom in yaw
K_{x}	Spring constant acting on Flying Boom extensible arm
B_{x}	Damping constant acting on Flying Boom extensible arm

3 Wedgetail Air-to-Air Refuelling Model

3.1 Prior Model

The flight model for the OFT is built up using Newton-Euler Equations of Motion (Baruh, H., 1999). With the forces and moments acting on the Ownship using the $\{\mathrm{OB}\}$ reference frame, orientated using the NASA Airplane standard convention (Duke, E.L. et al, 1988) and body fixed at the Centre of Mass (refer to Figure 1).

$$\{\mathrm{F}\} = [\mathrm{m}]\{\mathrm{a}\}$$

$$\{\mathrm{M}\} = [\mathrm{I}]\{\alpha\} + \{\omega\} \times ([\mathrm{I}]\{\omega\})$$

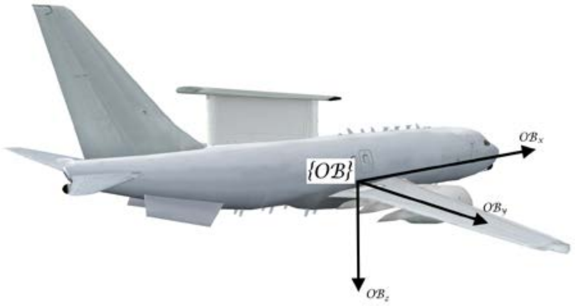

Figure 1 – Ownship Body Axis

The flight dynamics of the OFT are driven by modelling the forces and moments acting on the Ownship with contributions coming from the atmospheric model, the engine model, and the ground effect model.

$$\{M\} = \{M_{\text{aero}}\} + \{M_{\text{eng}}\} + \{M_{\text{gnd}}\}$$

$$\{F\} = \{F_{\text{aero}}\} + \{F_{\text{eng}}\} + \{F_{\text{gnd}}\}$$

Where

- F_{aero} and M_{aero} are the forces and moments resulting from the atmosphere model, contributing aerodynamic force and moment contributions to the dynamic model.
- F_{eng} and M_{eng} are the forces and moments resulting from the engine model, contributing the propulsion force and moment contributions to the dynamic model.
- F_{gnd} and M_{gnd} are the forces and moments resulting from the ground effect model, contributing the increased lift and decreased drag force and moment contributions to the dynamic model.

These force and moment contributions are fed into the Newton-Euler equations and the relationship is inverted to give the Ownship translative and rotational accelerations.

$$\{a\} = [m]^{-1}\{F\}$$

$$\{\alpha\} = [I]^{-1}\big(\{M\} - \{\omega\} \times ([I]\{\omega\})\big)$$

The approach taken to model the aerodynamic effects resulting from flight in the wake of the refuelling tanker was to modify the simulated atmosphere behind the Tanker to model the wake. This modification to the atmospheric model is depicted in Figure 2. The Tanker wake was modelled using empirical data collected by Boeing. The data is linearly interpolated between data points and linearly extrapolated to a set distance from the Tanker, providing a gradual introduction to the wake effects from free air when approaching the Tanker. This model results in modification of the F_{aero} and M_{aero} force and moment contributions to the dynamic model from the atmospheric model.

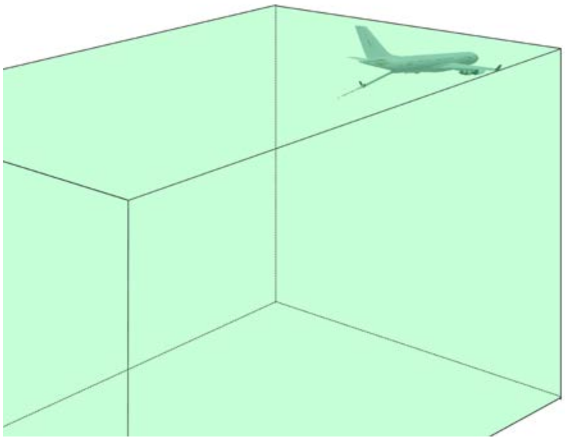

Figure 2 - Tanker Wake Field (not to scale)

3.2 Longitudinal Stability

As noted in Section 1, pilots have identified differences in the longitudinal stability response of the Ownship when in close proximity to the Tanker compared with the actual aircraft. This issue was described as, “from the astern position of the contact position for Tanking, the OFT is extremely sensitive to any thrust change made by the pilot”. This difference in fidelity between the OFT and the aircraft was leading to inappropriate thrust lever inputs in the OFT, both in size, rate and frequency, to maintain contact position with the Tanker. Essentially, pilots had to work harder to maintain contact in the simulator than in the real aircraft.

This was seen as introducing a negative training outcome for in contact tanking, due to the incorrect technique required to maintain contact with the Tanker. To overcome this fidelity gap, extra tuition was required to explain the differences between the OFT and the aircraft to the student. As a result, prior to this fidelity enhancement, long duration in contact tanking was not routinely trained to in the OFT, with a focus on approach to and initial contact with the Tanker instead.

On learning of the concern, an investigation was initiated by Thales. Discussions were held with the issue originators to extract details of the fidelity discrepancy. The details of the issue were then more widely discussed with other E-7A pilots with significant AAR expertise in order to gather a range of views on the fidelity gap. Armed with an understanding of the key concerns and finer details, a review of the Wedgetail OFT AAR modelling approach was conducted. It soon became apparent from both the review of the AAR model and discussions with the pilots that the root cause of the issue was a lack of dynamic feedback from the Flying Boom, which was not modelled, on the Ownship when in an ‘in contact latched’ position.

With the root cause of the issue identified, it was evident that an enhancement of the fidelity of the AAR model was required. Given there would be no opportunity to collect empirical data on the forces and moments exerted by the Flying Boom, and appropriate data from a supplier would be difficult to obtain, an alternative approach utilising a first principles dynamic model designed to enable subjective pilot tuning was required.

3.3 Fidelity Enhancement to Air-to-Air Refuelling Model

To account for the Flying Boom, force and moment contributions from the Ownship-Boom interaction were added to the Wedgetail OFT flight model.

$$\{\mathrm{F}\} = \{\mathrm{F}_{\text{aero}}\} + \{\mathrm{F}_{\text{eng}}\} + \{\mathrm{F}_{\text{gnd}}\} + \{\mathrm{F}_{\text{boom}}\}$$

$$\{\mathrm{M}\} = \{\mathrm{M}_{\text{aero}}\} + \{\mathrm{M}_{\text{eng}}\} + \{\mathrm{M}_{\text{gnd}}\} + \{\mathrm{M}_{\text{boom}}\}$$

Where F_{boom} and M_{boom} are the forces and moments exerted on the Ownship as a result of contact with the Flying Boom from the Tanker. These forces and moments are only exerted on the Ownship when in a ‘latched in contact’ position with the Flying Boom. At all other times their contribution is zero.

The assumption has been made that the forces and moments imparted onto the Tanker from the Ownship whilst ‘latched in contact’ are negligible due to the relative mass differences and the fact the Flying Boom pivots and extends to accommodate positional changes of the refuelling aircraft. It was also assessed by a Wedgetail AAR Subject Matter Expert that small disturbances on the Tanker from the Flying Boom interaction would not be perceptible to a Wedgetail Pilot. Thus, only the forces and moments acting on the

Ownship as a result of being ‘latched in contact’ with the Tanker needs to be modelled.

To assist with the construction of a dynamic model, body-fixed reference frames were defined (refer to Figure 3). The reference frame $\{\mathrm{TP}\}$ is body fixed and attached to the pivot point of the boom, orientated to the nominal boom angles for Air-to-Air Refuelling. The reference frame $\{\mathrm{TR}\}$ is body fixed and attached to the Universal Aerial Refuelling Receptacle Slipway Installation (UARRSI) interface point of the Flying Boom. The reference frame $\{\mathrm{OR}\}$ is body fixed attached to the UARRSI on the Ownship, orientated to the nominal boom angles for Air-to-Air Refuelling. The reference frame $\{\mathrm{OB}\}$ is body fixed attached to Centre of Mass of the Ownship, orientated for a standard airplane dynamic model.

Figure 3 – AAR Reference Frames

To model the magnitude of these forces ($\mathrm{F_{boom}}$) and moments ($\mathrm{M_{boom}}$), a 3 degree of freedom dynamic model of the Flying Boom was constructed. This model uses three generalised coordinates, boom pitch θ, boom yaw ψ, and boom extension x to describe the orientation and extension of the boom. The rotational coordinates were defined in the $\{\mathrm{TP}\}$ reference frame, the nominal tanking position for the boom, where deviations from the position would result in negative or positive changes in $\theta, \text{and } \psi$. The translative coordinate is defined from the maximum extent of the boom, where a decrease in boom extension results in a positive change in x. Refer to Figure 4 for the definition of the generalised coordinate system.

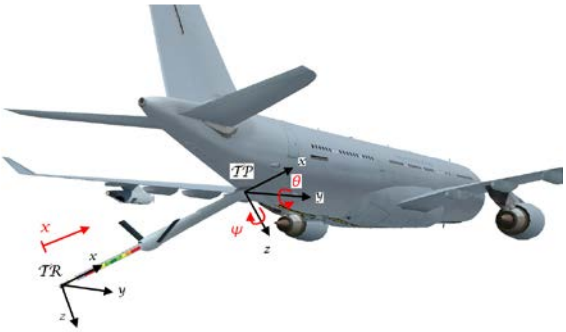

Figure 4 – Flying Boom Generalised Coordinates

The dynamics of these generalised coordinates were each modelled as a spring-damper system, giving a description of the forces of the Flying Boom in the $\{\mathrm{TR}\}$ reference frame as follows:

$$\tau_\theta = -\mathrm{K}_{r\theta}\theta - \mathrm{B}_{r\theta}\dot{\theta}$$

$$\tau_\psi = -\mathrm{K}_{r\psi}\psi - \mathrm{B}_{r\psi}\dot{\psi}$$

$$\mathrm{F_{TRx}} = -\mathrm{K}_x x - \mathrm{B}_x \dot{x}$$

$$\mathrm{F_{TRy}} = {}^{\tau_\psi}/_{\mathrm{d_b}}$$

$$\mathrm{F_{TRz}} = {}^{\tau_\theta}/_{\mathrm{d_b}}$$

Where

- τ_θ is the moment about the Flying Boom pivot in the pitch orientation,
- τ_ψ is the moment about the Flying Boom pivot in the yaw orientation,
- $\mathrm{F_{TR}}$ are the respective forces acting at the UARRSI interface of the Flying Boom in the $\{\mathrm{TR}\}$ reference frame,
- K are the spring constants for each of the generalised coordinates,
- B are the damping constants for each of the generalised coordinates, and
- $\mathrm{d_b}$ is the total length of the Flying Boom (including both the fixed and extensible part).

A simplifying assumption made is that the UARRSI interface is free to rotate. This in turn allows the UARRSI interface to be modelled as a spherical joint with three rotational degrees of freedom. This results in only forces being transferred to the UARRSI on Ownship by the Flying Boom.

With the forces acting on the UARRSI interface from the Flying Boom described in the $\{\mathrm{TR}\}$ reference frame we transform them to the $\{\mathrm{OR}\}$ reference frame to find the forces imposed on the Ownship from being ‘latched in contact’. This transform is achieved using the following Euler Angle Transform:

$$\{\mathrm{OR}\} = [\mathrm{R}_{321}]\{\mathrm{TR}\}$$

$$[\mathrm{R}_{321}] = [\mathrm{R}_3][\mathrm{R}_2][\mathrm{R}_1]$$

$$[\mathrm{R}_3] = \begin{bmatrix} \cos\psi_e & \sin\psi_e & 0 \\ -\sin\psi_e & \cos\psi_e & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$[\mathrm{R}_2] = \begin{bmatrix} \cos\theta_e & 0 & -\sin\theta_e \\ 0 & 1 & 0 \\ \sin\theta_e & 0 & \cos\theta_e \end{bmatrix}$$

$$[\mathrm{R}_1] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi_e & \sin\varphi_e \\ 0 & -\sin\varphi_e & \cos\varphi_e \end{bmatrix}$$

$$[\mathrm{R}_{321}] = \begin{bmatrix} \mathrm{c}\psi_e \, \mathrm{c}\theta_e & \mathrm{c}\theta_e \, \mathrm{s}\psi_e & -\mathrm{s}\theta_e \\ \mathrm{s}\varphi_e \, \mathrm{s}\theta_e \, \mathrm{c}\psi_e - \mathrm{c}\varphi_e \, \mathrm{s}\varphi_e & \mathrm{s}\varphi_e \, \mathrm{s}\theta_e \, \mathrm{s}\psi_e + \mathrm{c}\varphi_e \, \mathrm{c}\varphi_e & \mathrm{s}\varphi_e \, \mathrm{c}\theta_e \\ \mathrm{c}\varphi_e \, \mathrm{s}\theta_e \, \mathrm{c}\psi_e + \mathrm{s}\varphi_e \, \mathrm{s}\theta_e & \mathrm{c}\varphi_e \, \mathrm{s}\theta_e \, \mathrm{s}\psi_e + \mathrm{s}\varphi_e \, \mathrm{c}\psi_e & \mathrm{s}\varphi_e \, \mathrm{c}\theta_e \end{bmatrix}$$

Where $\mathrm{c}\psi_e$ is short hand for $\cos\psi_e$ and $\mathrm{s}\psi_e$ is short hand for $\sin\psi_e$.

The angles ψ_e, θ_e, and φ_e are the rotations required to rotate the $\{\mathrm{TR}\}$ Flying Boom body fixed reference frame to align with the UARRSI body fixed reference frame. This rotation takes into account the relative attitude differences between the Tanker and Ownship due to both these reference frames being body fixed to the respective aircraft.

Transforming the forces imparted by the Flying Boom is performed by the following equation:

$$\mathrm{F}_{\mathrm{OR}} = [\mathrm{R}_{321}]\mathrm{F}_{\mathrm{TR}}$$

where

$$\mathrm{F}_{\mathrm{OR}} = \begin{Bmatrix} \mathrm{F}_{\mathrm{ORx}} \\ \mathrm{F}_{\mathrm{ORy}} \\ \mathrm{F}_{\mathrm{ORz}} \end{Bmatrix}$$

$$\mathrm{F}_{\mathrm{TR}} = \begin{Bmatrix} \mathrm{F}_{\mathrm{TRx}} \\ \mathrm{F}_{\mathrm{TRy}} \\ \mathrm{F}_{\mathrm{TRz}} \end{Bmatrix}$$

With the forces now described in the $\{\mathrm{OR}\}$ reference frame, they are then transformed into the $\{\mathrm{OB}\}$ reference frame so they can be added to the Ownship flight model. We achieve this using the following Euler Angle Transform (refer to Figure 5 for a depiction of this transform).

$$[\mathrm{R}_{2'}] = \begin{bmatrix} \cos\theta_{\mathrm{B}} & 0 & -\sin\theta_{\mathrm{B}} \\ 0 & 1 & 0 \\ \sin\theta_{\mathrm{B}} & 0 & \cos\theta_{\mathrm{B}} \end{bmatrix}$$

$$\{\mathrm{OB}\} = [\mathrm{R}_{2'}]\{\mathrm{OR}\}$$

Transforming the forces into the $\{\mathrm{OB}\}$ reference frame is performed by the following equation:

$$\mathrm{F}_{\mathrm{OB}} = [\mathrm{R}_{2'}]\mathrm{F}_{\mathrm{OR}}$$

Where

$$\mathrm{F}_{\mathrm{OR}} = \begin{Bmatrix} \mathrm{F}_{\mathrm{ORx}} \\ \mathrm{F}_{\mathrm{ORy}} \\ \mathrm{F}_{\mathrm{ORz}} \end{Bmatrix}$$

$$\mathrm{F}_{\mathrm{OB}} = \begin{Bmatrix} \mathrm{F}_{\mathrm{OBx}} \\ \mathrm{F}_{\mathrm{OBy}} \\ \mathrm{F}_{\mathrm{OBz}} \end{Bmatrix}$$

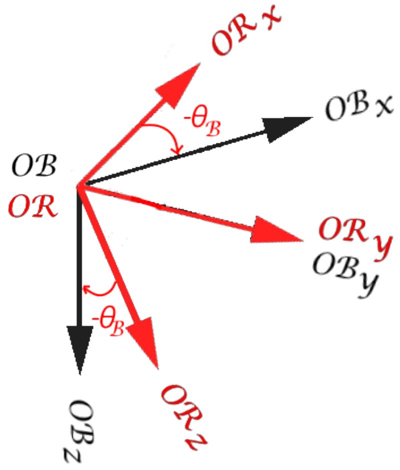

Figure 5 – {OR} to {OB} reference frame transform

Now that the forces acting on the Ownship due to the Flying Boom have been calculated in the $\{\mathrm{OB}\}$ reference frame, they can simply be added to the flight model for the Ownship as follows.

$$\{\mathrm{F}\} = \{\mathrm{F}_{\mathrm{aero}}\} + \{\mathrm{F}_{\mathrm{eng}}\} + \{\mathrm{F}_{\mathrm{gnd}}\} + \{\mathrm{F}_{\mathrm{boom}}\}$$

$$\{\mathrm{F}_{\mathrm{boom}}\} = \mathrm{F}_{\mathrm{OB}} = \begin{Bmatrix} \mathrm{F}_{\mathrm{OBx}} \\ \mathrm{F}_{\mathrm{OBy}} \\ \mathrm{F}_{\mathrm{OBz}} \end{Bmatrix}$$

Given the Flying Boom forces are applied to the Ownship at the UARRSI, moments about the Ownship centre of mass result from the application of these forces.

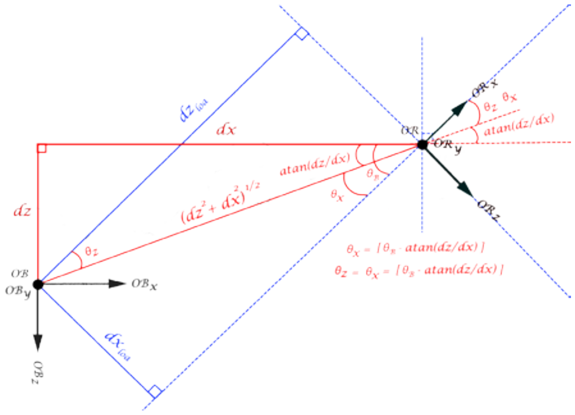

Figure 6 – Lines of Action

The geometry for the lines of action of the forces acting on the Ownship through the UARRSI are given in Figure 6. Using this geometry we arrive at the following equations describing the lines of action for the moments acting on the Ownship centre of mass.

$$\mathrm{dx}_{\mathrm{loa}} = (\mathrm{dx}^2 + \mathrm{dz}^2)^{1/2} \sin(\theta_{\mathrm{x}})$$

$$\mathrm{dz}_{\mathrm{loa}} = (\mathrm{dx}^2 + \mathrm{dz}^2)^{1/2} \cos(\theta_{\mathrm{z}})$$

With the lines of action described, we calculate the moments acting on the Ownship about the centre of mass as follows:

$$\mathrm{M_{OBx}} = 0$$

$$\mathrm{M_{OBy}} = \mathrm{F_{ORx}}.\mathrm{dx_{loa}} - \mathrm{F_{ORz}}.\mathrm{dz_{loa}}$$

$$\mathrm{M_{OBz}} = \mathrm{F_{ORy}}(\mathrm{dx}^2 + \mathrm{dz}^2)^{1/2}$$

With the moments acting on the Ownship now described in the $\{\mathrm{OB}\}$ reference frame, they can be added to the flight model for the Ownship as follows.

$$\{\mathrm{M}\} = \{\mathrm{M_{aero}}\} + \{\mathrm{M_{eng}}\} + \{\mathrm{M_{gnd}}\} + \{\mathrm{M_{boom}}\}$$

$$\{\mathrm{M_{boom}}\} = \mathrm{M_{OB}} = \begin{Bmatrix} \mathrm{M_{OBx}} \\ \mathrm{M_{OBy}} \\ \mathrm{M_{OBz}} \end{Bmatrix}$$

3.4 Subjective Tuning

With the dynamic model describing the Flying Boom interaction forces and moments imparted on the Ownship developed (refer to Section 3.3), subjective pilot tuning was used to arrive at the desired model fidelity for training purposes. Table 2 shows the model parameters that are available for adjustment and their respective effects on the Ownship forces and moments experienced due to the Flying Boom.

Table 2: Model parameters for tuning

Parameter	Effect on Model
$\mathrm{K_{r\theta}}$	As this increases, the Flying Boom will impart an increasing force to push the Ownship back to the nominal center in heave.
$\mathrm{B_{r\theta}}$	As this increases, the Flying Boom will impart an increasing force to resist motion from the Ownship in heave.
$\mathrm{K_{r\psi}}$	As this increases, the Flying Boom will impart an increasing force to push the Ownship back to the nominal center in sway.
$\mathrm{B_{r\psi}}$	As this increases, the Flying Boom will impart an increasing force to resist motion from the Ownship in sway.
$\mathrm{K_x}$	As this increases, the Flying Boom will impart an increasing force to push the Ownship back away from the Tanker in surge.
$\mathrm{B_x}$	As this increases, the Flying Boom will impart an increasing force to resist motion from the Ownship in surge.

During model development, it was discovered that if there was a large enough difference between the relative speeds of the Tanker and Ownship, upon initial contact with the Flying Boom, the instantaneous incorporation of the forces $\{\mathrm{F_{boom}}\}$ into the flight model resulted in a noticeable motion kick. To a pilot, this felt like an impact with the Flying Boom, and was too severe given small relative speed differences.

To minimise this effect and simulate a more subtle contact force in the motion during latching, ramp coefficients $\mathrm{F_{rmp}}$ and $\mathrm{M_{rmp}}$ were added to the model. A timer was also implemented to gradually incorporate the forces $\{\mathrm{F_{boom}}\}$ and moments $\{\mathrm{M_{boom}}\}$ into the flight model. $\mathrm{F_{rmp}}$ and $\mathrm{M_{rmp}}$ are defined between 0 and 1 and increase from an initial value, $\mathrm{F_{rmpinit}}$ and $\mathrm{M_{rmpinit}}$ respectively, to 1 over a set duration.

With the ramp value calculated, the flight model for the Ownship is modified as follows

$$\{\mathrm{F}\} = \{\mathrm{F_{aero}}\} + \{\mathrm{F_{eng}}\} + \{\mathrm{F_{gnd}}\} + \mathrm{F_{rmp}}.\{\mathrm{F_{boom}}\}$$

$$\{\mathrm{M}\} = \{\mathrm{M_{aero}}\} + \{\mathrm{M_{eng}}\} + \{\mathrm{M_{gnd}}\} + \mathrm{M_{rmp}}.\{\mathrm{M_{boom}}\}$$

This gives three more model parameters to tune, which affect the magnitude and timing of the introduction of the Forces and Moments acting on the Ownship as a result of the Flying Boom. Refer to Table 3 for a description of these model parameters.

Table 3: Additional model parameters for tuning

Parameter	Effect on Model
$\mathrm{F_{rmpinit}}$	Percentage of Forces to apply to the flight model instantaneously upon latch contact with the Flying Boom (defined from 0 to 1)
$\mathrm{M_{rmpinit}}$	Percentage of Moments to apply to the flight model instantaneously upon latch contact with the Flying Boom (defined from 0 to 1)
t_{rmp}	Duration in seconds for the ramp coefficients $\mathrm{F_{rmp}}$ and $\mathrm{M_{rmp}}$ to go from $\mathrm{F_{rmpinit}}$ to 1 and $\mathrm{M_{rmpinit}}$ to 1 respecitvely

There are now a set of 9 parameters available to tune the AAR model extension.

Subjective tuning of the AAR model was completed with an AAR Subject Matter Expert from the RAAF. During subjective tuning, it was found that $\mathrm{K_{r\theta}}$ and $\mathrm{K_{r\psi}}$ did not impart desirable feedback onto the Ownship and were zeroed, removing their impact from the model. Values for $\mathrm{B}_{\mathrm{r}\theta}$, $\mathrm{B}_{\mathrm{r}\psi}$, K_{x} and B_{x} were selected based on the subjective feel of the Ownship whilst Tanking in a latched position with the Flying Boom. These values gave the desired feedback on the Ownship from the Flying Boom and the longitudinal stability required for Training Outcomes. Similarly, values for $\mathrm{F}_{\mathrm{rmpinit}}$, $\mathrm{M}_{\mathrm{rmpinit}}$ and t_{rmp} were selected subjectively based on AAR SME feedback to give the desired initial contact forces on the Ownship.

4 CONCLUSION

The Wedgetail Operational Flight Trainer (OFT) provides a safe and cost effective AAR training capability using a high fidelity model. This model simulates the Tanker wake in the simulation environment and provides an accurate representation of the disturbances experienced by the Wedgetail during AAR manoeuvres. This allows for accurate approach and initial contact training in the OFT.

Recently, this AAR high fidelity model was enhanced to address a fidelity issue identified by Wedgetail aircrew. The root cause of this issue was identified as the Ownship force and moment interactions from the Flying Boom not being modelled. These interactions provide significant feedback on the Ownship, improving its stability when connected to the Tanker.

In the absence of empirical flight data and design data on the Flying Boom, Thales instead employed a dynamics based first principles approach designed to enable subjective tuning to modelling the interaction forces from the Flying Boom. This resulted in a set of parameters that were subjectively tuned by an AAR Subject Matter Expert from the Royal Australian Air Force (RAAF).

With the integration of this model into the Wedgetail OFT, Thales has significantly improved the AAR model fidelity for ‘in contact latched’ AAR. Having resolved the original issue with longitudinal stability during Tanking, combined with the existing AAR Tanker Wake model, the OFT provides a highly immersive training environment for complete AAR missions. The feedback on the enhanced AAR training capability in the OFT has been extremely positive from both End Users (RAAF) and the Instructors (Boeing Flight Services Australia).

This result demonstrates, that in appropriate circumstances, a dynamics based approach to modelling with careful design to enable subjective tuning, can provide significant training outcomes without requiring extensive data sets for parameter estimation of models.

5 ACKNOWLEGEMENTS

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