Improvements to the aerothermal modelling of object-oriented debris re-entry codes

Numerical and experimental progress

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4th International Workshop on Space Debris Re-entry
Thursday, 1st March 2018

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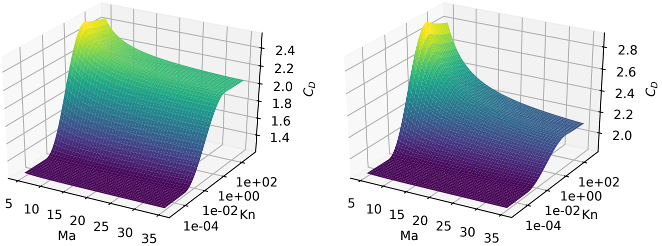
Contents

Numerical modelling of debris aerodynamics

Engineering level modelling

- RAC (Re-entry Aerodynamic Calculator) is used for analyses
- Standard multi-regime panel method formulation
  - Continuum: Modified Newtonian
  - Free molecular: Schaaf & Chambre
  - Transition: Wilmoth



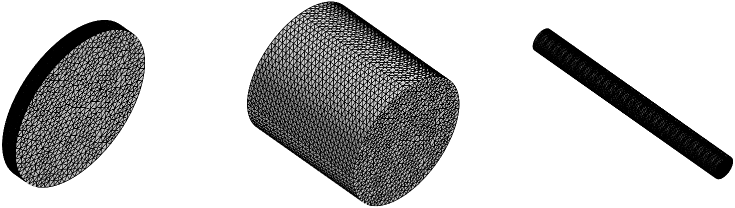
(a) Unit cylinder, $\alpha = 90^o$ (b) Unit cuboid, $\alpha = 90^o$

Figure 1: Mach-Knudsen surfaces for drag coefficient

Numerical modelling of debris aerodynamics

Common debris objects

- Triangulated surface meshes of a unit cylinder and cuboid
- Different aspect ratios are achieved by scaling along the longitudinal axis



(a) 1:10 (b) 1:1 (c) 10:1

Figure 2: Cylindrical meshes

Numerical modelling of debris aerodynamics

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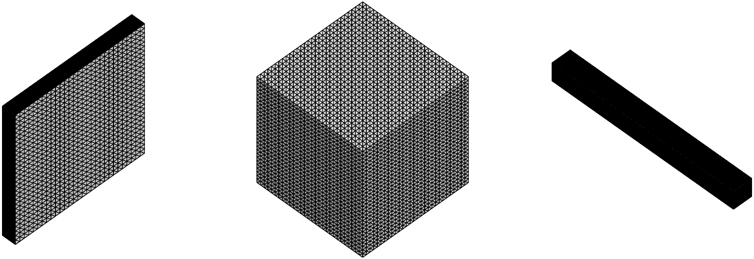

(a) 1:10 (b) 1:1 (c) 10:1

Figure 2: Cuboidal meshes

Numerical modelling of debris aerodynamics

Multidimensional correlation

- Kriging (1), a modified version of a Gaussian radial basis function, is utilised for correlative modelling
- Models are currently trained with calculations performed using RAC, but may be trained with data from any source (CFD, DSMC, experiments, etc.)
- A single model is used for each aerodynamic coefficient
- Prediction time varies depending on the complexity of the model
    - Number of training points
    - Number of dimensions

$$\psi^{(i)} = \exp\left(-\sum_{j=1}^{k} \theta_j |x_j^{(i)} - x_j|^{p_j}\right) \tag{1}$$

Numerical modelling of debris aerodynamics

Multidimensional correlation

- Two different types of Kriging models are being explored:
  - **Pure models**, wherein a single model with a high number of training points is used for each aerodynamic coefficient
  - **Augmented models**, wherein the Mach-Knudsen surface is modelled for each coefficient using a set of analytical expressions. The parameters of these surfaces are then correlated using a series of smaller Kriging models.
- Augmented models have been shown to have higher accuracy for a lower training point count
- Pure Kriging models are faster to evaluate (very useful if they are to be queried as part of a Monte Carlo calculation)
- Results presented today are produced using augmented models (pure models are still undergoing training)

Numerical modelling of debris aerodynamics

Correlation errors

- Cylindrical models are trained on 4 parameters
  - Mach, Ma
  - Knudsen, Kn
  - Pitch, α
  - Aspect, $\frac{L}{\varnothing}$
- A vector transform is used to convert Euler angles to a single equivalent pitch
- Absolute errors have been shown to be $< 6\%$

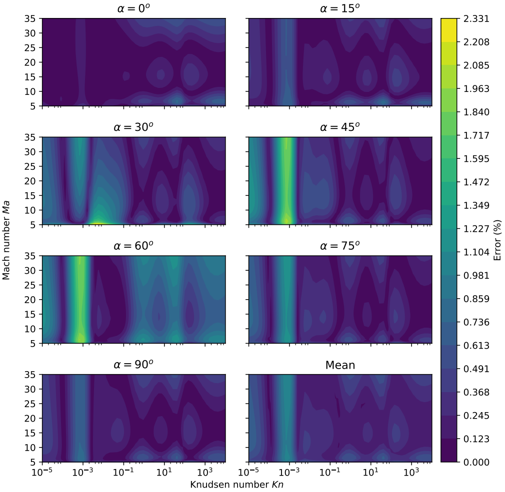

Figure 3: C_D errors for $\frac{L}{\varnothing} = 1$

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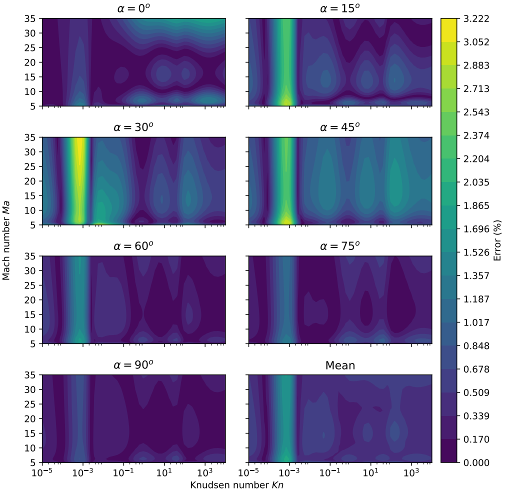

Figure 3: C_D errors for $\frac{L}{\varnothing} = 5$

Numerical modelling of debris aerodynamics

Correlation errors

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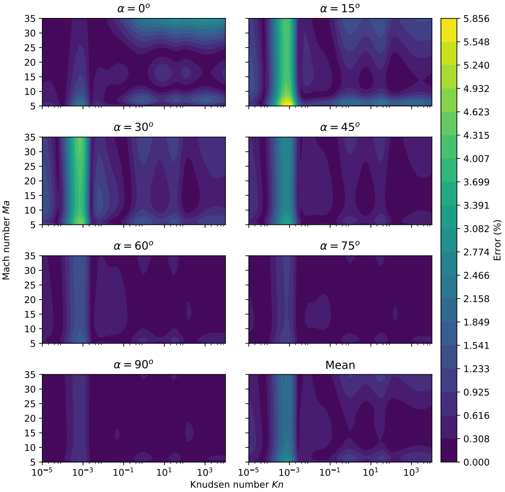

Figure 3: C_D errors for $\frac{L}{\varnothing} = 10$

Numerical modelling of debris aerodynamics

Correlation errors

- Cuboidal models are the most complex, and are trained on 6 parameters:
  - Mach, *Ma*
  - Knudsen, *Kn*
  - Pitch, α
  - Yaw, θ
  - Roll, β
  - Aspect, $\frac{L}{\varnothing}$

Numerical modelling of debris aerodynamics
Correlation errors

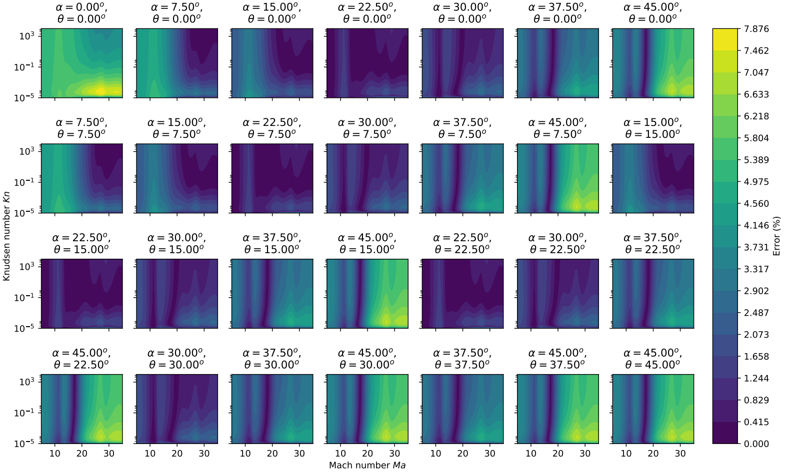

Figure 4: C_D errors for $\frac{L}{\varnothing} = 1$

Numerical modelling of debris aerodynamics

Correlation errors

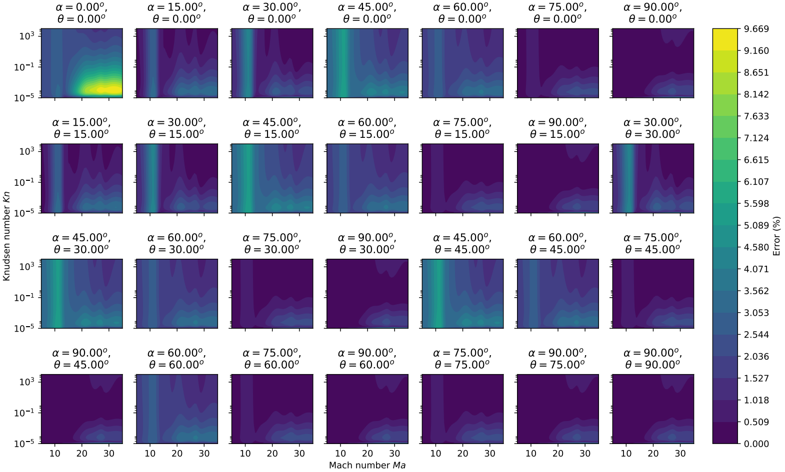

Figure 4: C_D errors for $\frac{L}{\varnothing} = 5$

Numerical modelling of debris aerodynamics
Correlation errors

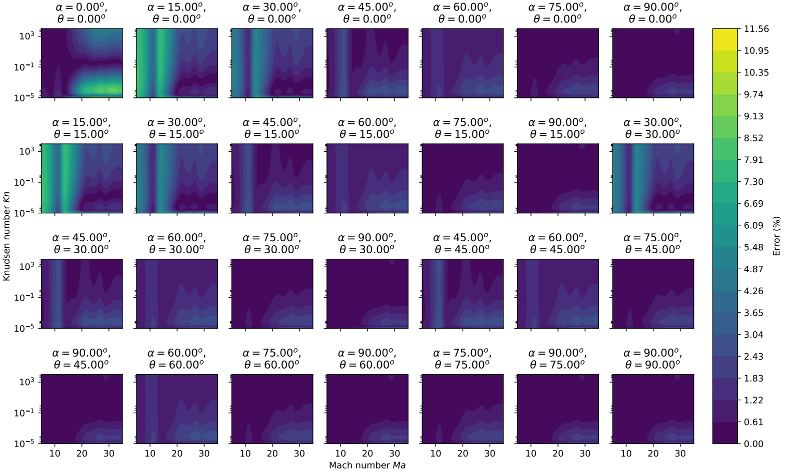

Figure 4: C_D errors for $\frac{L}{\varnothing} = 10$

Numerical modelling of debris aerodynamics
Future modelling

- Both augmented and pure Kriging models of a simplified ATV geometry are planned
- These will be trained on variances in pitch, α and yaw, θ

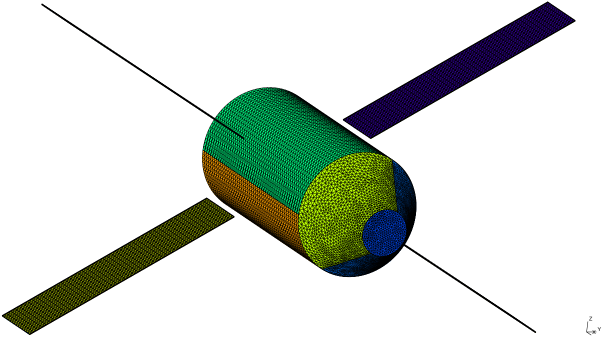

Figure 5: Surface mesh of a simplified ATV geometry

Experimental studies of thermal fluxes
Experimental facility

- The experimental facility being used is the Oxford Low Density Wind Tunnel (LDWT)
- 3 stage continuous vacuum pumping system (22000 l/s)
- Knudsen numbers of the order of ~ 0.001 (slip regime)
- Mach numbers ranging from $3 - 10$

Figure 6: The low density wind tunnel (LDWT)

Experimental studies of thermal fluxes
Experimental facility

- Working gas (air or nitrogen) is heated in an insulated stagnation chamber
- The gas is then expanded through a contoured Mach 6 nozzle into the test section
- Automated traverses control model position, and flow initialisation

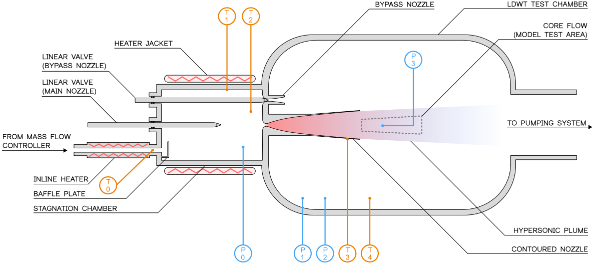

Figure 7: LDWT test section diagram

Experimental studies of thermal fluxes
Experimental facility

- The LDWT is currently undergoing characterisation activities following an extensive renovation
- These are set to conclude within the next few weeks

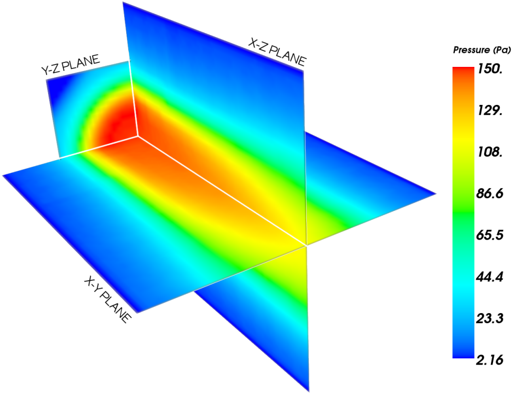

Figure 8: Total pressure pitot survey in the Mach 6 plume

Experimental studies of thermal fluxes
Thermochromatic liquid crystal studies

- Thermochromatic liquid crystal studies have been used at Osney for decades
- Current probes have been manufactured from Rohacell
- Three crystal solutions have been applied, with transition temperatures: $25^o C$, $30^o C$, and $35^o C$

Figure 9: Hemisphere LC probe undergoing a temperature change

Experimental studies of thermal fluxes

Platinum thin film gauge heat transfer probes

- Thin film gauge probes are manufactured using Macor glass ceramic
- Originally, gauges were painted onto the substrate by hand
- This arrangement led to transverse conduction issues inside the substrate, skewing thermal readings

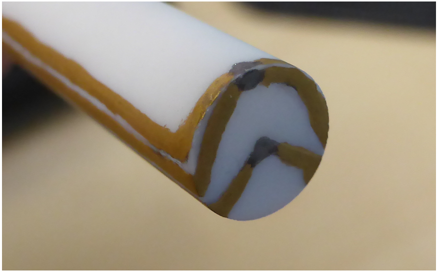

Figure 10: Original platinum paint TFG probe

Experimental studies of thermal fluxes
Platinum thin film gauge heat transfer probes

- The new design utilises precision printed gauges (details are accurate down to 5 μm)
- Gauges are sputtered using a vacuum deposition process
- Gauges are double-sided with a sheet of kapton between the two platinum layers, removing dependence on the substrate properties

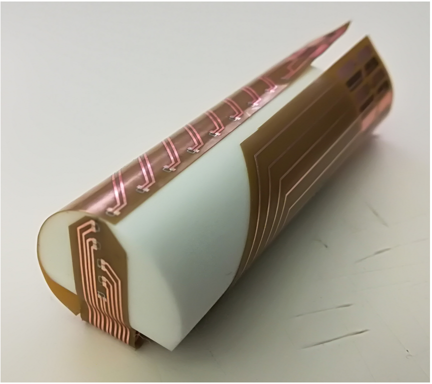

Figure 10: New sputtered TFG probe

Experimental studies of thermal fluxes

Probe sizes and gauge arrangements

- 9 LC probes have been manufactured
  - 3 shapes (hemisphere, cylinder, cuboid)
  - 3 sizes ($\varnothing 10\ mm$, $\varnothing 15\ mm$, $\varnothing 20\ mm$)
- 12 TFG probes have been manufactured
  - 2 shapes (cylinder, cuboid)
  - 3 sizes ($\varnothing 10\ mm$, $\varnothing 15\ mm$, $\varnothing 20\ mm$)
  - 2 probe arrangements (line over corner, line around edges)
- Differing sizes allow various Knudsen numbers to be examined without altering the freestream conditions

Experimental studies of thermal fluxes

Post processing of thermal flux data

- Constant current is applied to gauges from an amplifier
- Voltage changes are recorded as gauge temperatures change
- Calibration curves allow accurate conversion of change in voltage to change in temperature

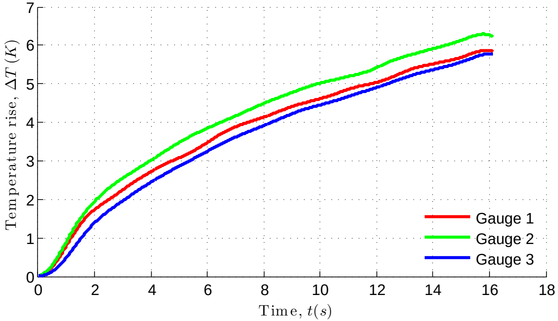

Figure 11: Typical temperature rise profile for thin film gauges

Experimental studies of thermal fluxes

Post processing of thermal flux data

- An impulse response filter is designed based upon the sampling frequency of the gauge data
- Temperature profiles are then processed through this filter, producing a heat flux profile
- Double-sided gauges remove all dependence on substrate properties

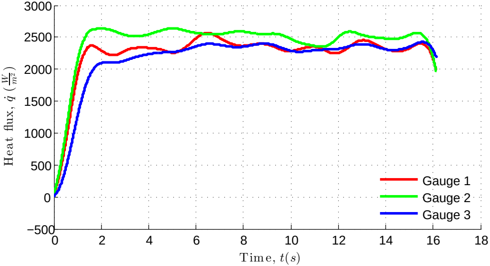

Figure 11: Typical heat flux profile for thin film gauges

Experimental studies of thermal fluxes

Post processing of thermal flux data

- Thermochromatic surveys are processed in a similar fashion
- Experimental runs are recorded visually using standard CCD or CMOS cameras
- An in-house code is used to analyse the colour changes against time
- A similar impulse response method is then used to convert these temperature changes into heat flux distributions

Conclusions

- Multidimensional correlative models are being generated for some common debris shapes
- These have been shown to have good accuracy and low run times
- They may be trained with cheap or expensive data (or any combination thereof)
- Experimental facility characterisation is almost complete following an extensive refit
- Experimental probes have been manufactured and are currently being assembled and tested

Thank you for your attention

Questions?

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