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Engine Inflow Boundary Conditions for Specification of Mass-Flow

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Abstract

Two engine inflow boundary conditions with direct specification of the integral quantities massflow and WAT respectively are formulated and implemented in the DLR *Tau*-code. For the formulation a summary of characteristic theory for the Euler equations is given, followed by the application of this theory to the derivation of several permeable boundary conditions with various flow quantities specified on the inflow surface. It is noted that the specification of a single integral quantity on the inflow face is insufficient to prescribe the flow there fully, and a remedy is proposed whereby the massflow distribution over the inflow boundary is obtained from the boundary near points. It is shown that this method is more efficient than specification of massflow by iteration on the inflow pressure, and has also less user-defined parameters. Similar results for the WAT boundary condition are given. Finally the relevant parameter settings as implemented in the *Tau*-code are described, and best-practice guidelines are given on the use of the new boundary conditions.

Contents

1 Introduction

Described are engine inflow boundary conditions which allow the direct specification of either the *massflow* $\dot{m}$ through the engine face, or the *WAT* Ω of the engine. Also described is their implementation and use in the DLR *Tau*-code [1]. The new boundary conditions are compared against a simple and robust boundary condition allowing direct specification of inlet pressure with respect to one Euler and two RANS test cases on the same ducted inlet geometry.

This report is divided into Chapter 2 which describes the derivation and particulars of the pressure, massflow and WAT boundary treatments; Chapter 3 which presents the performance and behavior of the boundary conditions in the already mentioned test cases. Users may wish to refer directly to Chapter 4 which contains a description of the relevant *Tau* parameters (Section 4.1), as well as some usage guidelines (Section 4.2).

1.1 Terminology

Throughout this report the terms *engine inflow* and *engine outflow* will be used to refer to surfaces where the flow passes out of the domain and into the domain respectively (i.e. into the engine and out of the engine). Another commonly used terminology is correspondingly *fan* and *exhaust*. It is assumed that the engine inflow flow is subsonic and unidirectional - given a supersonic inflow no specification of massflow is possible.

Due to the cell-vertex unstructured metric of the *Tau*-code grid points lie on the boundary; known as *boundary points*. For the purposes of extrapolation and reconstruction of values on the boundary from values lying strictly inside the domain, each boundary point has a corresponding *near point*, which is chosen to be as close to the boundary point as possible while lying in the direction normal to the boundary.

The fluid is modeled as a perfect gas throughout this document. Where physical quantities are used in this report they will be denoted as follows: ρ - density, u, v, w - the three components of velocity, U - velocity vector, V - $(U \cdot n)$ for some normal vector n, p - pressure, a - local speed of sound, t - time. Also flow quantities are normalized such that the gas constant R is equal to 1, so that the state equation becomes $p = \rho T$ for example.

Massflow and WAT may be defined as

$$\dot{m} = \iint \rho(U \cdot n)\, dA,$$

where the integral is over the engine face, n is the normal to the face and dA is a surface element, and

$$\Omega = \frac{\dot{m}\sqrt{\bar{T}_0}}{\bar{p}_0},$$

respectively, where $\bar{p}_0$ and $\bar{T}_0$ are the average total pressure and average total temperature *on the engine face.* The local values of those quantities may be written

$$\begin{aligned} p_0 &= p \cdot \left[1 + \frac{1}{2}(\gamma - 1)M^2 \right]^{\frac{\gamma}{\gamma-1}}, \\ T_0 &= T \cdot \left[1 + \frac{1}{2}(\gamma - 1)M^2 \right], \end{aligned}$$

where M is the local Mach number and γ is the ratio of specific heats. The dimensional units of the quantities are

$$\begin{aligned} \dot{m} &\rightarrow kg/s \\ \Omega &\rightarrow (kg\sqrt{K})/(kPa\, s) \end{aligned}$$

where the use of kilo-Pascals in the units of Ω should be noted.

2 Description of the Conditions

The characteristic theory of the Euler equations is briefly described, in particular as it relates to permeable boundary conditions. On this basis three boundary conditions are derived, identified by the single value that is specified on the subsonic inflow face. These are pressure, massflow, and WAT.

All three conditions are numerically strong, in that they set flow values on the boundary rather than fluxes; and they all rely on field data from the boundary near points.

2.1 Introduction to the Theory of Characteristics

In order to determine which flow values should to be set on a boundary, it is necessary to know which flow quantities are transported away from that boundary, and consequently also which are transported to the boundary. For the compressible Euler equations this information is provided by the theory of characteristics. A more complete discussion may be found in [2]. See Section 1.1 for a summary of the notation of the flow variables used here.

Note that this derivation makes two simplifying assumptions: firstly viscous effects are neglected, without which simplification the following is not possible; and secondly the role of the turbulence kinetic energy k that occurs in most two-equation turbulence models, and has an influence on the convective terms, is neglected for reasons of simplicity.

The derivation of the characteristic variables will be performed with respect to the primitive variables to simplify the procedure. The Euler equations in primitive variables, locally linearized with respect to a state W_0 are

$$\frac{\partial W_i}{\partial t} + A_{ij,k}(W_0)\frac{\partial W_j}{\partial x_k} = 0, \tag{2.1}$$

where the summation convention has been used on j and k, and

$$A_k\kappa_k = \begin{pmatrix} V & \kappa_x\rho & \kappa_y\rho & \kappa_z\rho & 0 \\ 0 & V & 0 & 0 & \kappa_x/\rho \\ 0 & 0 & V & 0 & \kappa_y/\rho \\ 0 & 0 & 0 & V & \kappa_z/\rho \\ 0 & \kappa_x\rho a^2 & \kappa_y\rho a^2 & \kappa_z\rho a^2 & V \end{pmatrix}, \qquad W = \begin{pmatrix} \rho \\ u \\ v \\ w \\ p \end{pmatrix}, \tag{2.2}$$

and κ is an arbitrary vector which fixes the direction in which we desire to know the information transport properties of the equations: for example when deriving boundary conditions κ is generally the surface normal vector. The eigenvalues of $A_k\kappa_k$ describe the speed of propagation of the various waves in the direction κ, the *characteristic speeds*, and are

$$\lambda = \left(\lambda^+, \lambda^-, \lambda^0, \lambda^0, \lambda^0\right),$$

where

$$\lambda^+ = U_k\kappa_k + a, \quad \lambda^- = U_k\kappa_k - a, \quad \lambda^0 = U_k\kappa_k.$$

The corresponding eigenvectors describe the quantities transported with these waves in terms of the primitive variables; they are the rows of the matrix X, where

$$X = \begin{pmatrix} 0 & \kappa_x & \kappa_y & \kappa_z & 1/(\rho a) \\ 0 & -\kappa_x & -\kappa_y & -\kappa_z & 1/(\rho a) \\ \kappa_x & 0 & \kappa_z & -\kappa_y & -\kappa_x/a^2 \\ \kappa_y & -\kappa_z & 0 & \kappa_x & -\kappa_y/a^2 \\ \kappa_z & \kappa_y & -\kappa_x & 0 & -\kappa_z/a^2 \end{pmatrix},$$

and result in the *characteristic variables* of transported quantities Λ, where

$$\Lambda = \begin{pmatrix} \Lambda^+ \\ \Lambda^- \\ \Lambda^0 \end{pmatrix} = X(W_0, \kappa) \cdot W = \begin{pmatrix} p/(\rho_0 a_0) + U \cdot \kappa \\ p/(\rho_0 a_0) - U \cdot \kappa \\ (\rho - p/a_0^2)\kappa + U \times \kappa \end{pmatrix}$$

$$= \begin{pmatrix} p/(\rho_0 a_0) + u\kappa_x + v\kappa_y + w\kappa_z \\ p/(\rho_0 a_0) - u\kappa_x - v\kappa_y - w\kappa_z \\ (\rho - p/a_0^2)\kappa_x + v\kappa_z - w\kappa_y \\ (\rho - p/a_0^2)\kappa_y + w\kappa_x - u\kappa_z \\ (\rho - p/a_0^2)\kappa_z + u\kappa_y - v\kappa_x \end{pmatrix}, \tag{2.3}$$

where $X(W_0, \kappa)$ again refers to the fact that the result is only valid linearly local to W_0, and with respect to the direction κ.

That the Λ are the transported quantities, with transport speeds λ may easily be seen by substituting (2.3) into the Euler equation in primitive variables (2.1), to obtain the Euler equations in characteristic variables:

$$\frac{\partial \Lambda_i}{\partial t} + \lambda_i \delta_{ij,k} \frac{\partial \Lambda_j}{\partial x_k} = 0,$$

where $\delta_{ij,k}$ is the Kroniker-Delta, repeated three times (on the index k), once for each coordinate direction, and there is no summation on i above.

Having now complete information about the characteristic speeds and variables, it is possible to derive permeable boundary conditions as follows: by considering the signs of the characteristic speeds, determine how many flow quantities are transported onto the boundary, and how many are transported away. For example in the case of an engine inflow the flow is subsonic in the direction of the boundary, hence λ^+ and λ^0 are positive while λ^- is negative, implying that Λ^+ and Λ^0 are transported onto the boundary from the field, and Λ^- is determined at the boundary. Hence one may choose a single flow variable to be set on the boundary termed the *physical boundary condition*; in general one must choose a set of variables corresponding to the number of negative eigenvalues[1].

[1] In fact the choice of variables to set is not completely free; it is obviously not allowable to set Λ^+ on an inflow boundary for example. See [2] for a complete discussion.

Having chosen a variable, or set of variables to specify on the boundary, the remaining flow quantities on the boundary are found as solutions of the *numerical boundary conditions*. Since the characteristic variables are transported directly onto the boundary, we must have

$$\Lambda_c^i(W_c) = \Lambda_b^i(W_c)$$

for all those Λ^i for which λ^i is positive. Here b signifies a point on the boundary, and c a point in the field not far from the boundary in the direction κ, i.e. in the surface normal direction. The linearization in the computation of the characteristic variables is performed with respect to the state at c. Specific examples of this calculation may be found in Sections 2.3 and 2.2.

2.2 Specification of Pressure

Consider the case of specifying the pressure p_{BC} on the inflow surface, whereby κ is chosen to be the surface normal vector n. This condition has been available in *Tau* for some time, having been developed by Melber and Widhalm [3]. Only a minor modification to the massflow coupling was needed for the purposes of massflow specification over a pressure iteration.

Following on from the previous section: the conditions at the boundary are then

$$\begin{aligned} p_b = p_{BC} \quad & \text{- one physical condition} \\ \Lambda_b^+(W_c) = \Lambda_c^+(W_c) \quad & \text{- one numerical condition} \\ \Lambda_b^0(W_c) = \Lambda_c^0(W_c) \quad & \text{- three numerical conditions} \end{aligned}$$

so that the numerical conditions expanded read

$$\begin{aligned} (U_b \cdot n) + p_b/(\rho_c a_c) &= \Lambda_c^+, \\ (\rho_b - p_b/a_c^2)n + U_b \times n &= \Lambda_c^0. \end{aligned}$$

By substituting p_{BC} for p_b in both equations, and taking the dot product of the second equation with n, a simple expression for ρ_b is obtained. An expression for U_b then follows directly giving:

$$W_b = \begin{pmatrix} \rho_b \\ U_b \\ p_b \end{pmatrix} = \begin{pmatrix} \Lambda_c^0 \cdot n + p_{BC}/a_c^2 \\ \left(\Lambda_c^+ - p_{BC}/(\rho_c a_c)\right) n + n \times \Lambda_c^0 \\ p_{BC} \end{pmatrix}, \tag{2.4}$$

whereby it has been noted that the tangential velocity component U_t satisfies

$$U_t = n \times \Lambda^0 = n \times (U \times n) = U - (U \cdot n)n.$$

Equation (2.4) may be simplified further by substituting in the expressions for the Λ_c, and is the desired boundary condition.

2.2.1 Iteration on the Massflow, varying Pressure

It is possible to obtain a boundary condition on the massflow from the above: the pressure is adjusted in accordance with the discrepancy between the actual and desired massflow until convergence is obtained. In particular

$$\begin{aligned} p_{BC}^n &= (1-\alpha)p_{BC}^{n-1} + \alpha(p_{BC}^{n-1} + \Delta p_{BC}), \\ \Delta p_{BC} &= \dot{m}_{actual}/\dot{m}_{desired} - 1, \end{aligned}$$

where α is a damping factor. Where it should be noted that Δp_{BC} is in fact scaled by the dimensionless reference pressure, which in this case is always 1.

2.3 Specification of Massflow

Now consider the case of directly setting the local massflow on the inflow surface, i.e. $[\rho(U\cdot n)]_{BC}$. From specification of local massflow a method for specifying global engine massflow may be constructed. Again from Section 2.1 the conditions at the boundary are

$$\begin{aligned} \rho_b(U_b \cdot n) &= [\rho(U\cdot\ n)]_{BC} && \text{- one physical condition} \\ \Lambda_b^+(W_c) &= \Lambda_c^+(W_c) && \text{- one numerical condition} \\ \Lambda_b^0(W_c) &= \Lambda_c^0(W_c) && \text{- three numerical conditions} \end{aligned}$$

with expanded numerical conditions identical to the case of specified pressure of

$$\begin{aligned} (U_b \cdot n) + p_b/(\rho_c a_c) &= \Lambda_c^+, \\ (\rho_b - p_b/a_c^2)n + U_b \times n &= \Lambda_c^0. \end{aligned}$$

By multiplying the first equation by ρ_b and substituting for the physical boundary condition the velocity vector is eliminated, leaving an equation with two unknowns: ρ_b and p_b. By taking the dot product of the second equation with n - as in Section 2.2 - the velocity vector there also eliminated. Hence two equations for two unknowns. By substitution the system may be reduced to one of two quadratic equations: one for ρ_b,

$$\left(\frac{a_c}{\rho_c}\right)\rho_b^2 - (U_c\cdot n + a_c)\,\rho_b + [\rho(U\cdot n)]_{BC} = 0, \tag{2.5}$$

and one for $\Delta p_b = p_b - p_c$,

$$\left(\frac{1}{\rho_c a_c^3}\right)\Delta p_b^2 + \frac{1}{a_c^2}(a_c - U_c\cdot n)\Delta p_b + ([\rho(U\cdot n)]_{BC} - \rho_c U_c\cdot n) = 0. \tag{2.6}$$

Of the two roots each of these equations (in the case where they have real roots) the lower corresponds to supersonic flow, and is therefore ignored. Given the solution for ρ_b or p_b the other value, and U_b may be easily obtained. For example in the case of use of the first quadratic equation:

$$W_b = \begin{pmatrix} \rho_b \\ U_b \\ p_b \end{pmatrix} = \begin{pmatrix} \rho_b^{sol} \\ (\Lambda_c^+ - p_b/(\rho_c a_c))\,n + n\times\Lambda_c^0 \\ p_c + \rho_c a_c\,(\rho_b U_c\cdot n - [\rho(U\cdot n)]_{BC})\,/\rho_b \end{pmatrix}$$

In the case where the equations predict negative density or pressure, or have no real roots, the value on the boundary is taken instead from the near point. In the case that the velocity vector points out of the engine inflow, it is set to zero.

2.3.1 Specification of Global Massflow

In the case of the fixed pressure condition the assumption of constant pressure on the inflow boundary is reasonable, except in extreme circumstances where e.g. vortices enter the inlet. Constant massflow however is not reasonable as - at least for viscous flows - there is often a boundary-layer entering the inlet.

In the absence of a user specified massflow profile, one is taken from the near points. The massflow distribution calculated at the near points is scaled by a global factor $\dot{m}_{desired}/\dot{m}_{nearpoint}$, and this is fixed on the engine plane for each iteration. This procedure places an extra burden on the regularity of the near points in comparison to the pressure based boundary condition.

2.4 Specification of WAT

The expression for the physical boundary condition in the case of direct local WAT specification is complicated by the presence of the total pressure and total temperature which have complex expressions in terms of the primitive flow variables. The boundary conditions are

$$
\begin{aligned}
\rho_b(U_b \cdot n)\sqrt{T_{0,b}}/p_{0,b} &= [\rho(U \cdot\ n)\sqrt{T_0}/p_0]_{BC} && \text{- one physical condition} \\
\Lambda_b^+(W_c) &= \Lambda_c^+(W_c) && \text{- one numerical condition} \\
\Lambda_b^0(W_c) &= \Lambda_c^0(W_c) && \text{- three numerical conditions.}
\end{aligned}
$$

It is no longer possible to derive an analytic expression for the primitive variables on the boundary from the above equations, leaving two approaches: either perform the solution numerically using Newton's method or similar, or treat some component of the boundary condition as constant - taking its value from the existing boundary, and iterate to a stationary state.

Newton's method is costly and can be unreliable. On the other hand by treating $\sqrt{T_0}/p_0$ as a constant, the boundary condition reduces to that of Section 2.3. This may be justified in part by considering that for an isentropic inviscid flow p_0 is constant and variations in T_0 are small.

The condition is hence implemented as follows: the value of $\sqrt{T_0}/p_0$ on the engine face is calculated and based on this and the given fixed WAT value, a provisional massflow is calculated. The boundary treatment according to constant massflow is applied and the field updated, resulting in an achieved WAT value. As may be seen in Section 3, the achieved WAT value converges rapidly to the fixed WAT value with few oscillations, validating the reasoning given here.

3 Results

The boundary conditions described have been implemented in the *Tau* code and are tested here with respect to three challenging test cases of practical engineering interest. The three cases are based on the same geometry, with one Euler mesh and calculation, and two Navier-Stokes calculations with one coarse and one fine mesh. The geometry and pressure distribution for the Euler calculation are shown in Figures 3.1. The case represents the forward part of the fuselage of a fighter aircraft, with a total of three inflow boundaries, which are identified by a thick black border - there is no outflow in this case. The main inlet is buried deep within the body, reached by a twisting duct from the outlying collector. Due to the duct, the flow reaching the main engine face will be complex and feature-rich, including boundary layers, vortices and possibly regions of separated flow. Also the inlet face defines the flow outside the collector, some distance away, meaning that a change at the inflow boundary will take many iterations to affect the outer field, reducing the efficiency of iterative strategies for massflow specification.

In each case - as a point of reference for the convergence of the calculation with the new massflow and WAT boundary conditions - the fixed pressure boundary condition is used, with the inflow pressures specified by the values found in a constant massflow calculation. Hence if the boundary conditions are appropriately implemented the resulting fields should be similar (not identical due to the constant pressure assumption in the pressure boundary condition), and the convergence also comparable. Where a WAT calculation has been performed the WAT values on the faces were also obtained from a previous fixed massflow calculation.

Figure 3.2 shows the convergence of three calculations on the Euler mesh: one calculation for each of the boundary conditions, whereby all three engine inflow faces use the same boundary condition in each computation. The Mach number is 0.3, at an angle of attack of $3.0°$. The massflows through the main, second and third engine faces are set to 30.0, 6.0 and 1.2 kg/s respectively. After the fixed massflow calculation the face pressures where found to be about 1.01×10^5, 9.19×10^4 and 5.45×10^4 Pascals respectively, and the engine WAT values 4.80, 1.04 and 0.20 $kg\sqrt{K}/(kPa\, s)$ respectively. Detailed parameter settings are given in Section 4.3 and the calculation was performed on 32 processors of a Xeon Linux cluster; the grid has about 165 thousand points.

As may be seen from the figure, the convergence - in terms of the residual - is similar for all boundary conditions, indicating that the massflow boundary condition has an efficiency comparable to that of the pressure condition. The discrepancy in the resulting massflow and WAT in the case of the pressure calculation is due to the constant inflow pressure assumption, which seems to be especially invalid in the case of the second engine face.

Exactly the same calculation has been performed for the coarse viscous test case with additionally a Reynolds number of 8×10^6 and the one-equation Spalart-Allmaras-Edwards turbulence model; the grid has roughly one million points. The results are given in Figure 3.3. As in the previous case the convergence of all three calculations with the various boundary conditions are nearly identical, and the convergence of the various engine quantities also proceeds as expected. In summary the new boundary conditions perform almost as well as the existing fixed pressure

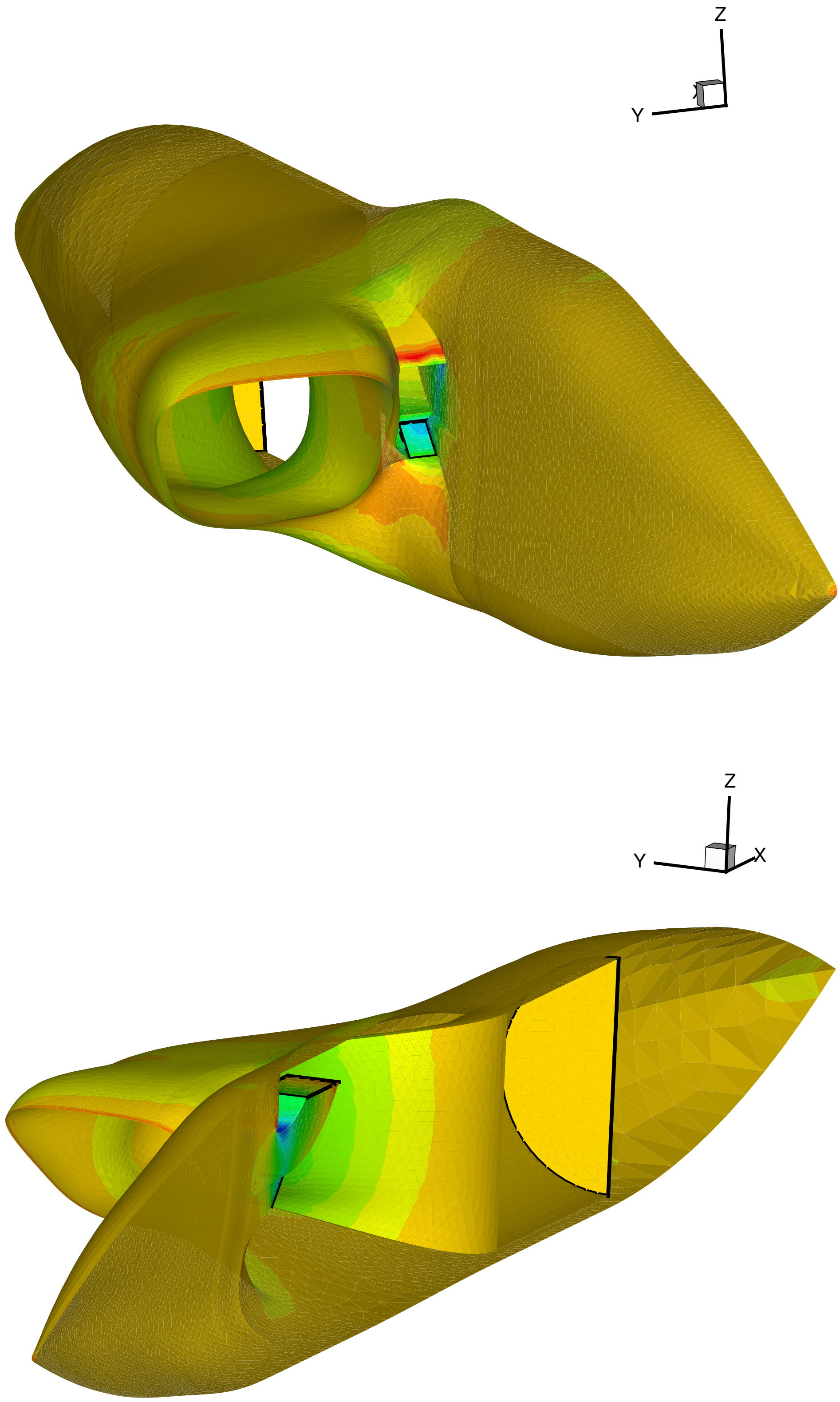

Figure 3.1: The test case geometry; the fuselage of a fighter aircraft with two minor inlets and one ducted main inlet (bordered in black).

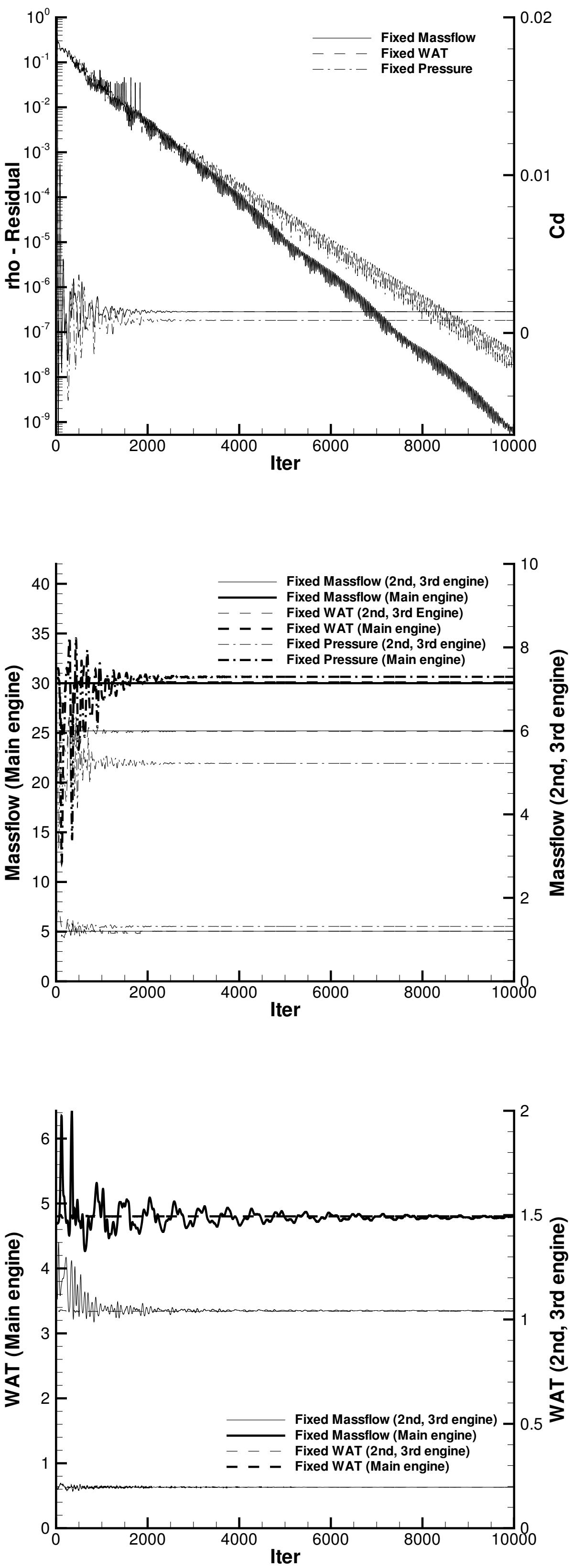

Figure 3.2: Convergence of three calculations with three different engine boundary conditions for the inviscid case. Shown are ρ-residual and drag coefficient, massflow and WAT.

condition for this case.

The final test consists of the calculation of two flows on a fine viscous grid about 4.4 million points. The two cases differ only in the angle of attack, 3° and 5°, of which the latter cause separation of the boundary layer within the main engine inlet. The specified engine quantities on the inflows are, for the main, second and third engine faces, 8.45 $kg\sqrt{K}/(kPa\,s)$, 6.27 kg/s and 0.59 kg/s respectively, so a combination of massflow and WAT. The convergence of the two cases is shown in Figure 3.4, with a calculation using the fixed pressure condition with values obtained after the massflow calculation. As for the previous cases the convergence of the new boundary condition is almost identical to that of the pressure-based condition, indicating a robust and efficient method.

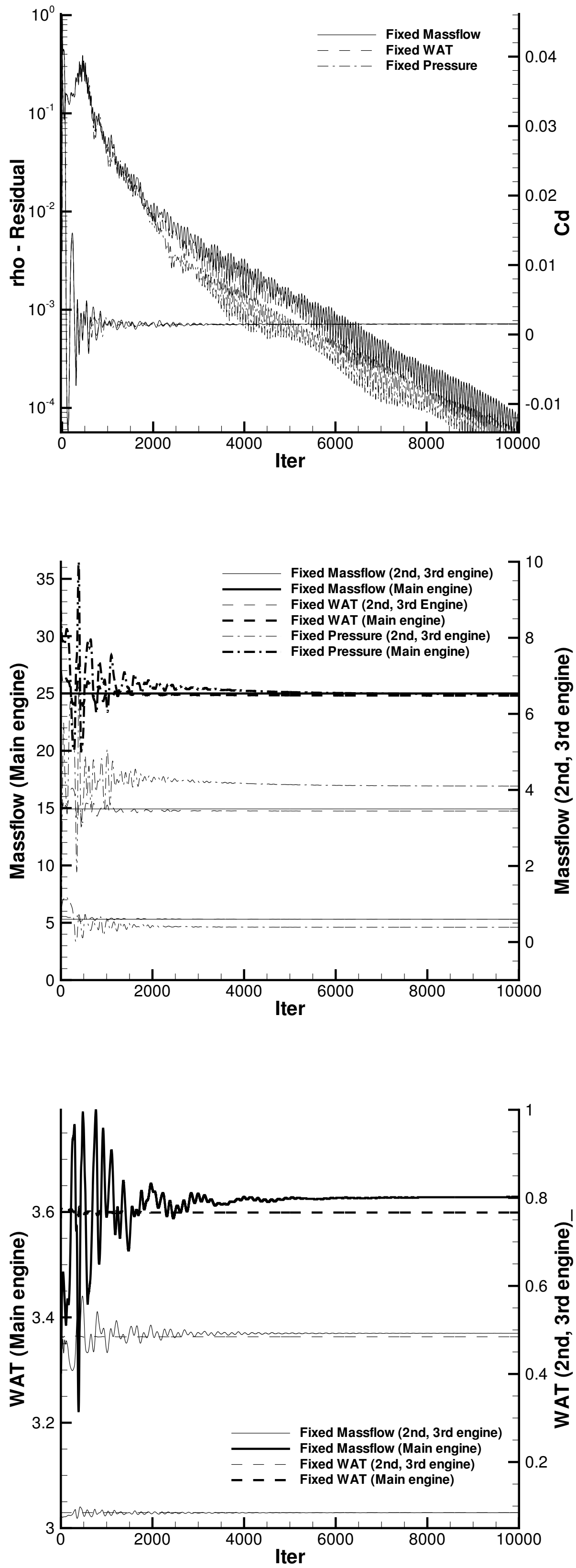

Figure 3.3: Convergence of three calculations with three different engine boundary conditions for the viscous case on the coarse grid. Shown are ρ-residual and drag coefficient, massflow and WAT.

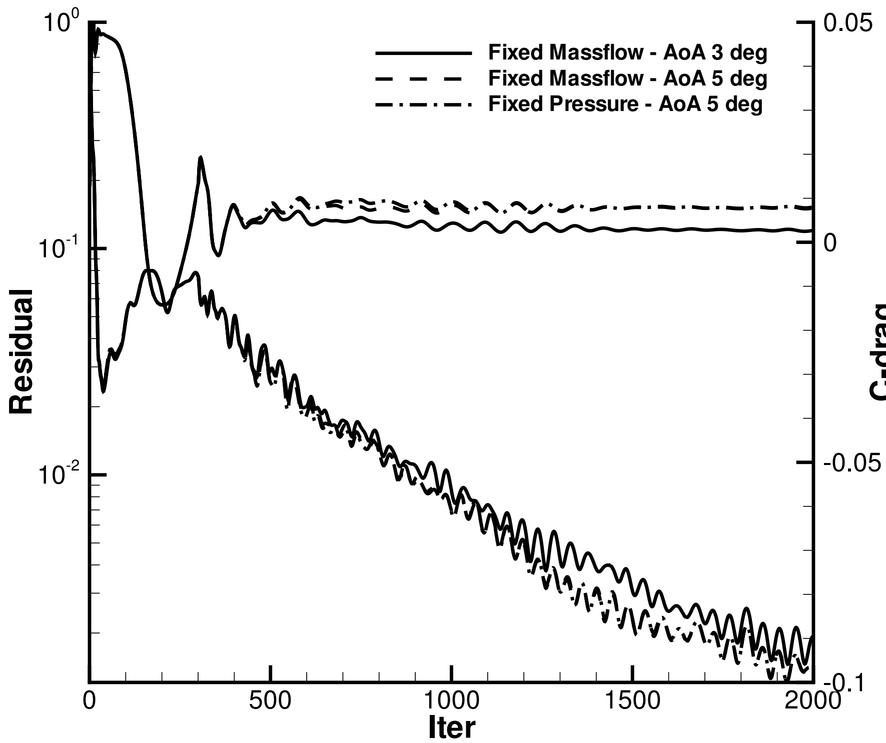

Figure 3.4: Convergence of two calculations with at two angles of attack a viscous case on the fine grid. Shown are ρ-residual and drag coefficient.

4 Engine Boundary Condition User Guide

While a complete description of the parameters pertaining to the engine boundary conditions is given in the *Tau* User Guide [4], for reference they are described here. An additional section describes some general tips for use of the treatments.

4.1 Parameter Input

In addition to the parameters that apply to all *Tau* boundary conditions:

Type:, Markers:, Name:

Write surface data (0/1):

Cutting plane allowed (0/1):

and whose functions are described in the *Tau* User Guide [4], the following parameters apply to all engine inflow boundaries (`Type: engine inflow`):

Engine number: Specify the engine to which this inflow boundary belongs. The concept of engines is most useful when performing massflow coupling of an inlet massflow to an outlet massflow, i.e. when using the `Fixed_pressure` inflow type with the `Outflow_massflow` coupling type. Only one inflow boundary may be assigned to each engine.

Inflow condition type: One of `Fixed_epsfan`, `Fixed_pressure` or `Fixed_massflow`. The type of inflow condition is characterized by the variable that is set on the boundary during the enforcement of the condition - not the variable that is specified by the user. For example it is possible for the user to specify massflow using the pressure condition by means of an outer iteration. Depending on the condition chosen different parameters are available, described below. In the context of this report `Fixed_pressure` refers to Section 2.2, and `Fixed_massflow` to Sections 2.3 and 2.4. `Fixed_epsfan` refers to a condition based on Laval-fan theory, not described in this here, see [3].

Engine inflow direction: Set the normal vector to the inflow face. This vector will be used everywhere in the code in place of the true normal vector, e.g. the massflow integration. The default is the averaged boundary normal vector, which is taken if the parameter is not given, or if it is given as the zero vector.

Monitor mass flow (0/1): In monitoring output (stdout), print the dimensional total mass inflow through this boundary.

Monitor pressure (0/1): In monitoring output, print the dimensional averaged pressure on the inflow boundary.

Monitor WAT (0/1): In monitoring output, print the dimensional value of WAT on the inflow boundary.

If the inflow condition type is chosen to be `Fixed_epsfan` the following parameter becomes available:

Area ratio eps_fan: Inverse ratio of the fan inflow area to the respective area in the undisturbed region. This boundary treatment requires the existence of a farfield boundary.

If the type is chosen to be `Fixed_pressure` either the pressure or the massflow may be specified by the user over the following:

Type of mass coupling: Type of iteration used to obtain desired massflow; one of `None`, `Outflow_massflow` or `Fixed_massflow`. If `None` is chosen the pressure is fixed to the given value. If `Outflow_massflow` is chosen, there must exist an engine outflow boundary with the same engine number as this inflow. In this case the inflow pressure is iterated according to Section 2.2.1 until parity of inflow and outflow massflow is obtained. If `Fixed_massflow` is chosen the pressure is iterated until the massflow specified by the parameter "Fixed massflow" is achieved.

Fixed/initial pressure: The dimensional pressure to be fixed on the inflow for all iterations (if using no mass coupling), or initially (otherwise).

Pressure from restart file (0/1): If the calculation is based on a restart, decide whether the initial pressure on the inlet is determined by the "Fixed/initial pressure" parameter, or the average of the pressure on the inlet in the restart file. Default is 1.

Relaxation factor: Relaxation factor α of Section 2.2.1.

Fixed massflow: If the mass coupling type is `Fixed_massflow`, the (dimensional) massflow to obtain by iteration.

If `Fixed_massflow` type is chosen either the massflow or the WAT may be specified by the user using the following:

Fixed massflow: The desired dimensional massflow through the inflow. Only one of "Fixed massflow" or "Fixed WAT" may be given.

Fixed WAT: The desired dimensional WAT on the inflow boundary. Only one of "Fixed massflow" or "Fixed WAT" may be given.

Extrapolation type simple/characteristic (0/1): Use the characteristic treatment described in Section 2.3 (recommended), or a simplified boundary condition that may be more robust for nearly supersonic inflow speeds.

Solve quadratic eqn for rho/p (0/1): Choose whether the quadratic equation (2.5) or (2.6) should be solved in determining the boundary flow values.

Note that where flow quantities are specified over parameters, they are always dimensional.

4.2 Suggestions for Use

4.2.1 Grid Generation

As stated in Section 1.1 and seen in Section 2.1, the near points to the surface play an important role in constructing the boundary condition - especially for the new fixed massflow condition. These points are chosen by the preprocessor to be as close as possible to the boundary points in the surface normal direction. This choice is greatly facilitated by a prismal layer normal to the inflow or outflow surface. Experience shows that such a grid considerably improves the stability and performance of the calculation as a whole, and is strongly recommended [3].

4.2.2 Lower Limit for Massflow

There is often a lower limit on the massflow that may be specified through an inflow surface that will lead to a stable *Tau* solution. Taking the test case of Section 3 for example, and replacing the inflow surfaces with Euler walls, i.e. a zero massflow, the calculation diverges rapidly. This is due to the resulting configuration having a closed cavity whose opening faces the oncoming flow; an extremely unstable state independent of the particular boundary condition used. Similarly specifying too low a massflow through an inflow surface may also result in cavity flow: the only recourse being a full unsteady calculation.

4.2.3 Choice of Condition for Specified Massflow

There are two means of specifying the inflow massflow, via the `Fixed_pressure` condition with the `Fixed_massflow` iteration, and simply the `Fixed_massflow` condition. Due to the great simplicity of the pressure boundary condition it may be stabler for a wider range of engine settings and starting conditions than the massflow condition - whose internal quadratic equation is not guaranteed to have a real or a positive solution, (2.5). On the other hand the iterative procedure need to specify a given massflow with `Fixed_pressure`, as well as the sensitivity of said iteration to the relaxation parameter α, means that is method is likely to be less efficient, especially in the long duct case seen here, where the coupling between the engine face and the outer flow is relatively weak. In summary: used fixed massflow initially, and only if it fails to converge, move onto fixed pressure.

4.2.4 Full-multigrid and Fixed Massflow

As discussed in Section 2.3.1, the regularity of the near points play a more important role for the fixed massflow condition than for other boundary treatments. In the case of multigrid the near points are particularly poorly positioned, and therefore the boundary condition is switched off on the coarse grids during a normal multigrid cycle, and the local multigrid corrections are set to zero. In the case of the full-multigrid start-up method however, the boundary condition must be evaluated on the coarse grids initially - and as been seen in at least one case to cause divergence of the calculation there. Therefore no full-multigrid with the fixed massflow condition is recommended.

4.2.5 LU-SGS Coarse Grid CFL Number

Not relating to the presently discussed boundary condition, but as a matter of general interest: it has recently become known to the author that the LU-SGS scheme in combination with multigrid can stall if the coarse grid CFL number is too large. In particular for Runge-Kutta time-stepping a coarse grid CFL number of 1.7 times the fine grid CFL number is default and recommended. In contrast for LU-SGS a coarse grid CFL number of about half the fine grid CFL must be provisionally recommended - especially in cases where the convergence stalls. This setting has no effect on the speed of multigrid convergence, and has been seen to sometimes improve it. This is now the default setting in *Tau*.

4.3 Example Parameter File

A *Tau* parameter file used in the above Euler calculations is given here as an example.

```
 -----------------------------------------------------
 BOUNDARY MAPPING
 -----------------------------------------------------
            Markers: 1-5, 7
               Type: euler wall
               Name: SecondEngChannel
 block end
 ---------------------------
            Markers: 6, 8-13, 22, 24-35, 52
               Type: euler wall
               Name: ForwardFuselage
 block end
 ---------------------------
            Markers: 14, 16-21, 23, 42
               Type: euler wall
               Name: MainEngChannel
 block end
 ---------------------------
            Markers: 15
               Type: engine inflow
                       Name: SecondEngFace
      Engine number: 2
          Monitor mass flow (0/1): 1
           Monitor pressure (0/1): 1
        Monitor WAT (0/1): 1
            Inflow condition type: Fixed_pressure
                   ###Fixed massflow: 6.0
                Fixed WAT: 1.043
## If Fixed_massflow
 Extrapolation type simple/characteristic (0/1): 1
              Massflow constant on inflow (0/1): 0
            Solve quadratic eqn for rho/p (0/1): 0
## If Fixed_pressure
            Type of mass coupling: None
   Fixed/initial pressure: 9.187e4
                Relaxation factor: 0.05
    Massflow convergence residual: 1e-4
 block end
 ---------------------------
            Markers: 36, 53
               Type: symmetry plane
               Name: Symmetry
 block end
 ---------------------------
```

```
                     Markers: 37
                        Type: engine inflow
                        Name: ThirdEngFace
              Engine number: 3
    Monitor mass flow (0/1): 1
     Monitor pressure (0/1): 1
        Monitor WAT (0/1): 1
            Inflow condition type: Fixed_pressure
                   ###Fixed massflow: 1.2
                Fixed WAT: 1.963e-1
## If Fixed_massflow
 Extrapolation type simple/characteristic (0/1): 1
              Massflow constant on inflow (0/1): 0
            Solve quadratic eqn for rho/p (0/1): 0
## If Fixed_pressure
            Type of mass coupling: None
   Fixed/initial pressure: 5.446e4
                Relaxation factor: 0.05
    Massflow convergence residual: 1e-4
 block end
 ---------------------------
            Markers: 38, 39, 40, 41, 43
               Type: farfield
Angle alpha (degree): 3.0
               Name: Farfield
 block end
 ---------------------------
            Markers: 44, 46, 47, 48, 49, 51
               Type: euler wall
               Name: RearFuselage
 block end
 ---------------------------
                     Markers: 45
                        Type: engine inflow
                        Name: MainEngFace
              Engine number: 1
    Monitor mass flow (0/1): 1
     Monitor pressure (0/1): 1
        Monitor WAT (0/1): 1

            Inflow condition type: Fixed_pressure
                   ###Fixed massflow: 30.0
             Fixed WAT: 4.802
## If Fixed_massflow
 Extrapolation type simple/characteristic (0/1): 1
              Massflow constant on inflow (0/1): 0
            Solve quadratic eqn for rho/p (0/1): 0
## If Fixed_pressure
      Type of mass coupling: None
             Fixed/initial pressure: 1.010e5
  Relaxation factor: 0.05
      Massflow convergence residual: 1e-4
 block end
 ---------------------------
            Markers: 50
               Type: symmetry plane
               Name: EngSymmetry
```

```
block end
---------------------------

-----------------------------------------------------
Required Parameters
-----------------------------------------------------
           Boundary mapping filename: ./Intake2g.bmap
               Primary grid filename: ./Intake2g_vol.tau
                               Reference Mach number: 0.3
                                     Reynolds number: 8.e6
                                     Reynolds length: 1.0
                                         Grid scale : 1.0

-----------------------------------------------------
IO
-----------------------------------------------------
                                         Grid prefix: ./dualgrid
                                 Output files prefix: ./Log_A
   Solver --------------------------------------------: -
                    Automatic parameter update (0/1): 0
                 Write pointdata dimensionless (0/1): 0

-----------------------------------------------------
PREPROCESSING
-----------------------------------------------------
                          Number of multigrid levels: 3
                        Bandwidth optimisation (0/1): 0
                      Number of primary grid domains: 32
                                   Number of domains: 32
                         Type of partitioning (name): private
                          Compute lusgs mapping (0/1): 1
   Agglomeration-------------------------------------: -
                                 Point fusing reward: 1.2
                          Structured grid coarsening: 0
                          Sharp edge angle (degrees): 0
               Cache-coloring (0/max_faces in color): 10000
-----------------------------------------------------
SOLVER
-----------------------------------------------------
                    Solver type upwind/central (0/1): 1
                               Increase memory (0/1): 1
                           First order upwind solver: Roe
                          Second order upwind solver: Roe
                                Gradient computation: Green_Gauss

                      Order of basic equations (1/2): 2
                 Order of additional equations (1/2): 1
                     Lowest pressure for 2nd order: 0.001
                      Lowest density for 2nd order: 0.001
   Solver/Dissipation -----------------------------: -
                          Central matrix dissipation: 0.5
                     Central classic dissipation 2nd: 0.5
          #  Inverse central classic dissipation 4th: 64
             Inverse central classic dissipation 4th: 8
            Central classic dissipation 2nd (coarse): 0.125
                            Ausm scheme dissipation: 0.25
   Timestepping Start/Stop ------------------------: -
```

```
                                 Output period: 10000
                      Maximal time step number: 10000
                              Minimum residual: 1.e-10
                             Relaxation solver: Backward_Euler
                                    CFL number: 1.0
                     CFL number (coarse grids): 0.4
MG----------------------------------------------: -
                       MG description filename: 3w
            SG start up steps (fine grid): 300
                Interpolate corrections (0/1): 0
                        Multigrid start level: 1
          Maximal time step number (coarse grids): 100
                  Minimum residual (coarse grids): 0.01
Geometry ----------------------------------------: -
                      Reference relation area : 115.59
             Reference length (pitching momentum): 9.29
       Reference length (rolling/yawing momentum): 9.29
                   Origin coordinate x        : 0.0
                   Origin coordinate y        : 0.0
                   Origin coordinate z        : 0.0
References --------------------------------------: -
   Reference temperature : 288.16
```

5 Conclusion

Two boundary conditions have been implemented for modelling engine inflow boundaries; one allowing the direct specification of the total massflow through the engine, and the other the specification of the engine WAT value. Both have been seen to be superior to alternative conditions based on variation of pressure and a target massflow, and converge at a similar rate to a boundary condition implementing specification of pressure at the inflow face.

The details of both conditions have been described, as well as their implementation in the *Tau*-code, in particular the relevant new parameters. Advice on best-practices for these boundary conditions has been given.

Bibliography

[1] T. Gerhold, M. Galle, O. Friedrich, and J. Evans. Calculation of complex 3D configurations employing the DLR TAU-Code. *AIAA Paper, AIAA-97-0167*, 1997.

[2] C. Hirsch. *Numerical Computation of Internal and External Flows: Fundamentals of Numerical Discretization v. 1.* John Wiley and Sons Ltd, 1989. ISBN 0471923850.

[3] S. Melber-Wilending. Modifikation der triebwerkrandbedingung und einfuehrung einer windkanalranbedingung in tau. *DLR Institutsbericht, IB 124-2003/7*, 2003.

[4] Various. *DLR Tau-code User Guide.*

IB 124-2006/6

Engine Inflow Boundary Conditions for Specification of Mass-Flow

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