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# RANS calculations of the flow through an elliptically loaded actuator disk

*David Hally*

**Defence R&D Canada – Atlantic**

Technical Memorandum
DRDC Atlantic TM 2010-126
July 2010

Canada

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# Abstract

In preparation for calculating effective wakes by replacing a propeller with an embedded force field, the DRDC Atlantic flow solver TRANSOM has been modified to allow for mass and momentum source terms in the Reynolds-averaged Navier-Stokes equations. The modifications have been validated using three flows for which analytic solutions are available: unidirectional flow with a Gaussian mass source distribution, unidirectional flow with a Gaussian momentum source distribution, and flow through an elliptically loaded actuator disk. The latter flow was also calculated using ANSYS CFX. In all cases the agreement with the analytic solutions was very good.

# Résumé

Pour calculer des sillages efficaces en remplaçant une hélice par un champ de force intégré, le solutionneur d'écoulement TRANSOM de RDDC Atlantique a été modifié pour qu'il tienne compte des termes de sources de masse et d'impulsion dans les équations de Navier-Stokes en moyenne de Reynolds. Les modifications ont été validées d'après trois écoulements pour lesquels il existe des solutions d'analyse : écoulement unidirectionnel avec distribution normale de la source de masse, écoulement unidirectionnel avec distribution normale de la source d'impulsion et écoulement à travers un disque actuateur à charge elliptique. Ce dernier écoulement a également été calculé avec le logiciel CFX d'ANSYS. Dans tous les cas, la correspondance avec les solutions d'analyse s'est avérée très grande.

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# Executive summary

## RANS calculations of the flow through an elliptically loaded actuator disk

David Hally; DRDC Atlantic TM 2010-126; Defence R&D Canada – Atlantic; July 2010.

**Background:** The Maritime Asset Protection Section at DRDC Atlantic is using Reynolds-averaged Navier-Stokes (RANS) solvers to predict the flow around propellers so that the noise generated by propeller cavitation can be predicted. An important feature of this modelling problem is that there is an interaction between the flows around the ship hull and the propeller, which can be taken into account by introducing a force field into the calculation of the flow around the hull. The force field mimics the thrust of the propeller.

**Principal results:** To be able to predict the hull-propeller interaction, the DRDC Atlantic flow solver TRANSOM was modified so that it could predict the flow generated by an arbitrary force field. The modifications were tested using three flows for which analytic solutions are known. The most demanding test, and the one which most closely mimics a propeller, was the flow through an elliptically loaded actuator disk. The commercial flow solver ANSYS® CFX® was also used to model this flow. In all cases agreement between the computed and analytic solutions was excellent.

**Future work:** The modified code will be used to study the effect of propeller-hull interaction on propeller performance, in particular, the development of cavitation and radiated noise caused by it.

# Sommaire

## RANS calculations of the flow through an elliptically loaded actuator disk

David Hally ; DRDC Atlantic TM 2010-126 ; R & D pour la défense Canada – Atlantique ; juillet 2010.

**Introduction :** La Section de la protection des biens maritimes de RDDC Atlantique recourt à des solutionneurs d'équations de Navier-Stokes en moyenne de Reynolds (Reynolds-Averaged Navier-Stokes – RANS) pour prévoir l'écoulement autour d'hélices et le bruit produit par la cavitation des hélices. Un des éléments importants de ce problème de modélisation est l'interaction entre les écoulements autour de la coque d'un navire et l'hélice, dont on peut tenir compte en intégrant un champ de force reproduisant la poussée de l'hélice dans le calcul de l'écoulement autour de la coque.

**Résultats :** Pour prévoir l'interaction entre la coque et l'hélice, le solutionneur d'écoulement TRANSOM de RDDC Atlantique a été modifié pour prévoir l'écoulement produit par un champ de force arbitraire. Les modifications ont été mises à l'essai d'après trois écoulements dont on connaît les solutions d'analyse. L'essai le plus exigeant et celui qui reproduit le mieux une hélice est l'essai d'écoulement à travers un disque actuateur à charge elliptique. Le solutionneur d'écoulement commercial ANSYS® CFX® a aussi servi à modéliser cet écoulement. Dans tous les cas, la correspondance entre les solutions calculées et les solutions d'analyse s'est avérée très grande.

**Perspectives :** Le code modifié servira à étudier l'effet de l'interaction entre la coque et l'hélice sur le rendement de l'hélice et, plus particulièrement, le développement de la cavitation et le bruit rayonné produit par cette dernière.

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# 1 Introduction

At DRDC Atlantic the inflow to a propeller can be calculated using one of two Reynolds-averaged Navier-Stokes (RANS) solvers: TRANSOM, developed at DRDC Atlantic [1,2]; or ANSYS® CFX® [3]. The flow around the propeller can be calculated using either of these programs as well as by two panel method programs: PROCAL, developed by the Co-operative Research Ships (CRS) consortium; or ASP, developed at DRDC Atlantic.

The interaction between the flows around the hull and the propeller is commonly taken into account by introducing a force field into the calculation of the flow around the hull [4,5,6]. The force field mimics the thrust of the propeller, accelerating the flow upstream and influencing the boundary layer and separation region near the stern. The propeller inflow including the interaction effect is usually called the effective wake. The CRS PROPDEV Working Group is currently investigating this type of procedure for calculating the effective wake. For DRDC Atlantic to take full advantage of the PROPDEV research program, it is necessary to be able to make RANS calculations with embedded force fields.

This report briefly describes the implementation of a force field capability within TRANSOM, then validates both TRANSOM and ANSYS CFX for the flow through an elliptically loaded actuator disk for which there is an analytical solution [7].

# 2 The implementation of force fields in TRANSOM

The RANS equations can be written:

$$\frac{\partial v_i}{\partial x_i} = M \tag{1}$$

$$\frac{\partial v_i}{\partial t} + v_j \frac{\partial v_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu_t\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i})\right)\right] + S_i \tag{2}$$

where the Einstein convention of summing over repeated indices is used. Here $v_i$ are the components of the fluid velocity, $p$ is the pressure, $\rho$ is the fluid density (constant since TRANSOM only treats incompressible flows), $\nu_t$ is the turbulent viscosity which is determined using an appropriate turbulence model, $M$ is a mass source, and $S_i$ are the components of a specific momentum source (i.e. a rate of change of momentum divided by the density; units of acceleration).

A force field can be implemented by making $S_i$ non-zero. As pointed out by Hally and Laurens [8], mass source terms may also be necessary to account for the fact that the

RANS solvers calculate the flow both inside and outside the propeller blades. Note that the inclusion of $M$ is not intended to model compressible flows; many additional changes would be required for that. Therefore no bulk viscosity coefficient has been included in the model.

The continuity equation can be used to recast the momentum equations to the following form:

$$\frac{\partial v_i}{\partial t} + \frac{\partial (v_j v_i)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu_t \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)\right] + S_i + M v_i \tag{3}$$

TRANSOM already includes a method for assigning the values of $S_i$. It is used, for example, for adding Coriolis and centrifugal forces when the coordinate system is rotating. To implement arbitrary force fields, it was simply necessary to allow the values of $S_i$ at each grid node to be set from a global variable that can be read from an input file. A similar change was made to allow $M$ to be set in an arbitrary way.

# 3 Verification cases

Three different verification cases were used to test that the source terms have been implemented correctly.

## 3.1 Laminar unidirectional flow with Gaussian mass sources

The first test case is laminar unidirectional flow in an unbounded domain with a Gaussian distribution of mass sources near the origin. This was solved in TRANSOM both as a two-dimensional and a three-dimensional flow with identical results. Here we assume that the flow is two-dimensional with $v_x \equiv v_x(x)$, $v_y = 0$, $p \equiv p(x)$ and

$$M = \frac{\Delta v \, e^{-(x/\Delta x)^2}}{\sqrt{\pi}\,\Delta x} \tag{4}$$

The steady Navier-Stokes equations then reduce to

$$\frac{\partial v_x}{\partial x} = M \tag{5}$$

$$v_x \frac{\partial v_x}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + 2\nu \frac{\partial^2 v_x}{\partial x^2} \tag{6}$$

With $v_x = v_0$ far upstream and $p = 0$ far downstream, these equations are easily solved to yield:

$$v_x = v_0 + \Delta v \,\mathrm{erf}(x/\Delta x); \qquad \frac{p}{\rho} = \tfrac{1}{2}\Big[(v_0 + \Delta v)^2 - v_x^2\Big] + 2\nu M \tag{7}$$

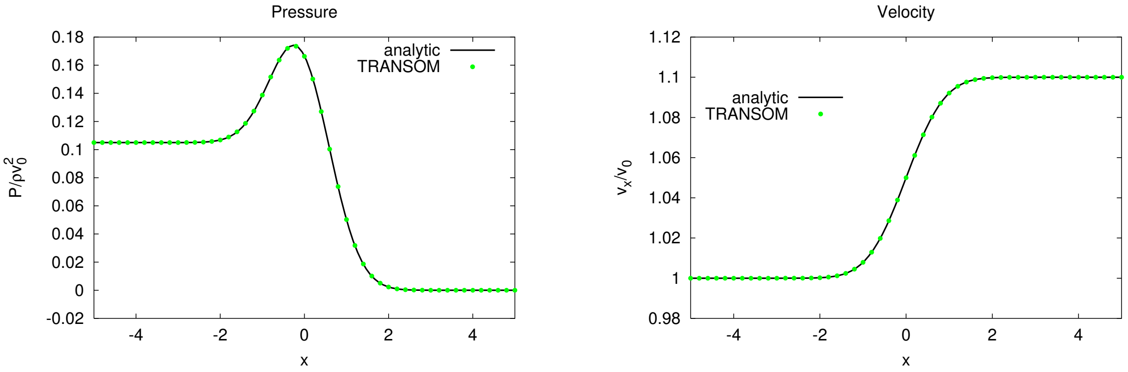

***Figure 1:*** *The variation of pressure and velocity as a function of $x$ for the unidirectional flow with Gaussian mass sources.*

The flow was solved on a uniform $101 \times 11$ rectangular grid over the region $x \in [-10\text{m}, 10\text{m}]$, $y \in [-5\text{m}, 5\text{m}]$ with $v_0 = 1\text{m/s}$, $\Delta v = 0.1\text{m/s}$, $\nu = 1\text{m}^2/\text{s}$, $\Delta x = 1\text{m}$ and $\rho = 1\text{kg/m}^2$. The result is compared with the analytic solution in Figure 1.

## 3.2 Laminar unidirectional flow with Gaussian momentum sources

The second test case is laminar unidirectional flow in an unbounded domain with a Gaussian distribution of momentum sources near the origin. This was solved in TRANSOM both as a two-dimensional and a three-dimensional flow with identical results. Here we assume that the flow is two-dimensional with $v_x \equiv v_x(x)$, $v_y = 0$, $p \equiv p(x)$ and

$$S_x = \frac{\Delta p \, e^{-(x/\Delta x)^2}}{\sqrt{\pi}\, \rho \Delta x}; \qquad S_y = 0 \tag{8}$$

Since there are no mass sources, the continuity equation implies that $v_x$ is constant. The pressure is then simply the integral of the momentum sources:

$$p = \tfrac{1}{2}\Delta p\Big(\text{erf}(x/\Delta x) - 1\Big) \tag{9}$$

The flow was solved on the same grid as the preceding test case with with $v_0 = 1\text{m/s}$, $\Delta p/\rho = 1\text{m}^2/\text{s}^\text{s}$, $\nu = 1\text{m}^2/\text{s}$, $\Delta x = 1\text{m}$ and $\rho = 1\text{kg/m}^2$. The result is compared with the analytic solution in Figure 2.

## 3.3 Elliptically loaded actuator disk

Actuator disks have long been used to model the induction of propellers and fans. Conway [7] provides an analytic expression for the flow through an actuator disk with

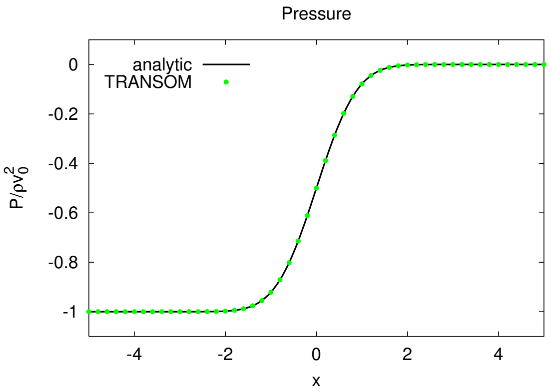

***Figure 2:*** *The variation of pressure as a function of $x$ for the unidirectional flow with Gaussian momentum sources.*

elliptical loading, under the approximation that the slipstream downstream of the disk does not contract. This approximation limits the solution to light loading. The velocity field of the actuator disk is:

$$V_x(x,r) = V_\infty + \frac{V_0 x}{R}\arcsin\left(\frac{2R}{\sqrt{x^2+(R+r)^2}+\sqrt{x^2+(R-r)^2}}\right) + \begin{cases} V_0\alpha, & x \le 0 \\ \dfrac{2V_0\sqrt{R^2-r^2}}{R} - V_0\alpha, & x \ge 0, \quad r \le R \\ -V_0\alpha, & x \ge 0, \quad r \ge R \end{cases} \tag{10}$$

$$V_r(x,r) = \frac{V_0|x|}{2r}\left(\frac{1}{\alpha}-\alpha\right) - \frac{V_0 r}{2R}\arcsin\left(\frac{2R}{\sqrt{x^2+(R+r)^2}+\sqrt{x^2+(R-r)^2}}\right) \tag{11}$$

$$\alpha = \sqrt{\frac{\sqrt{(R^2-r^2-x^2)^2+4x^2R^2}+R^2-r^2-x^2}{2R^2}} \tag{12}$$

Along a radial line in the actuator disk one has

$$V_x(0,r) = V_\infty + \begin{cases} \dfrac{V_0\sqrt{R^2-r^2}}{R}, & r \le R \\ 0, & r \ge R \end{cases} \tag{13}$$

$$V_r(0,r) = \begin{cases} \dfrac{\pi V_0 r}{4R}, & r \le R \\ \dfrac{V_0 r}{2R}\arcsin\left(\dfrac{R}{r}\right), & r \ge R \end{cases} \tag{14}$$

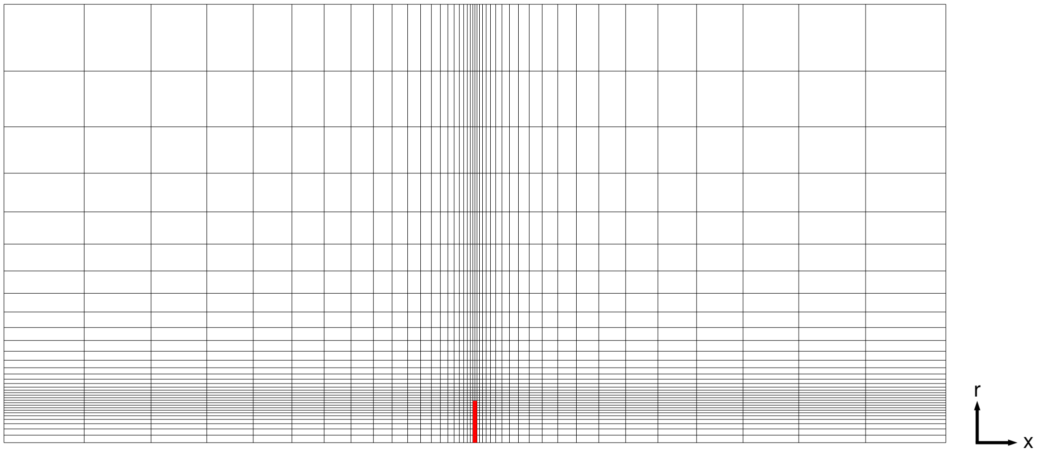

***Figure 3:*** *An example of the node clustering in the axisymmetric two-dimensional grid. The red line shows the location of the actuator disk.*

and along the $x$ axis

$$V_x(x,0) = V_\infty + V_0 + \frac{V_0 x}{R} \arcsin\left(\frac{R}{\sqrt{x^2+R^2}}\right) \tag{15}$$

$$V_r(x,0) = 0 \tag{16}$$

The loading is given by

$$S_x = 2\rho V_x(0,r)\Big(V_x(0,r) - V_\infty\Big)\delta(x) \tag{17}$$

TRANSOM was used to solve the flow on a two-dimensional grid using the axisymmetric flow model, and also on a three-dimensional grid. The radius of the disk was $R = 1$m, the free stream flow was $V_\infty = 1$m/s, and the induced flow at the centre of the disk was $V_0 = 0.1$m/s. In each case the momentum source terms were smeared in the $x$ direction using a Gaussian distribution of half-width $\Delta x$:

$$S_x(r) = 2V_x(0,r)\Big(V_x(0,r) - V_\infty\Big)\frac{e^{-(x/\Delta x)^2}}{\sqrt{\pi}\Delta x} \tag{18}$$

The two-dimensional grid was an $85 \times 386$ rectangular grid covering the region $x \in [-11.25R, 11.25R]$, $r \in [0, 10.5R]$. The nodes were concentrated near the plane of the disk ($x = 0$) and near the its edge ($r = R$), with the smallest cell dimension being $0.001R$. The half-width of the source density distribution was $\Delta x = 0.01R$. Figure 3 shows a less dense version of the grid to illustrate the concentration of nodes.

Figures 4 and 5 compare the TRANSOM predictions with the analytic solutions. The smearing of the momentum sources has been accounted for in the analytic curves by weighting the velocity by the Gaussian distribution and integrating Equations (10)

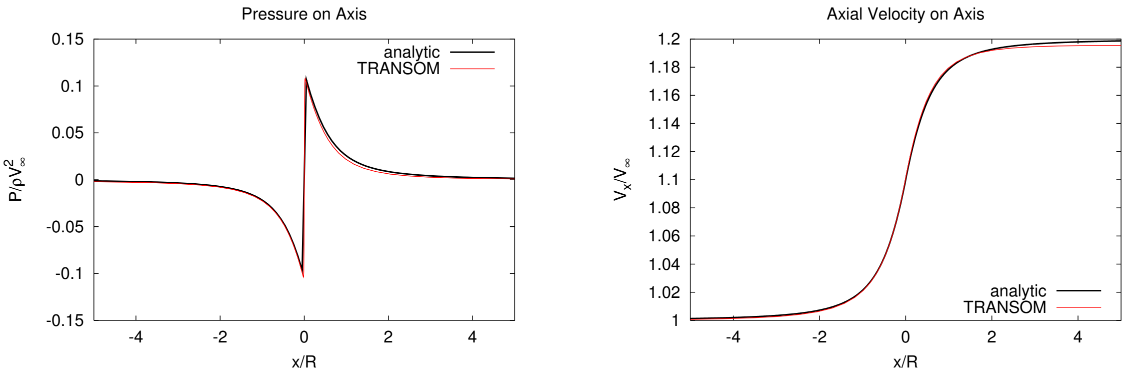

**Figure 4:** *Comparison of the TRANSOM predictions on a two-dimensional grid with analytic curves for the pressure and axial velocity along the x-axis.*

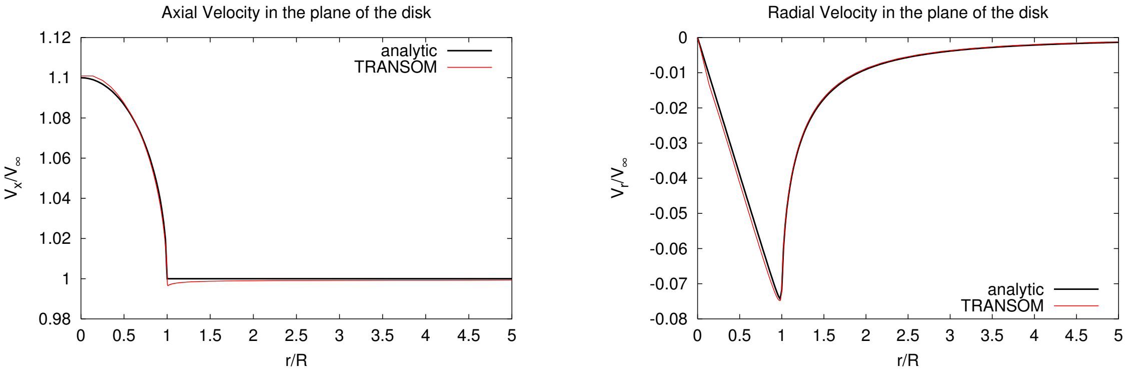

**Figure 5:** *Comparison of the TRANSOM predictions on a two-dimensional grid with analytic curves for the velocity in the plane $x = 0$.*

and (11) numerically in the axial direction. The difference between the integrated curves and the expressions for an infinitely thin disk are very small except for the case of the radial velocity near the edge of the disk.

The agreement between the TRANSOM predictions and the analytic solutions are good. The predicted axial velocity in the plane of the actuator disk (left side of Figure 5) shows an overprediction of the axial velocity on the axis and a small underprediction when $r$ is just larger than $R$. These features are almost certainly due to the neglect of the slipstream contraction in the analytic solution. Conway has also calculated this case including the effect of slipstream contraction [9]; both features are present in his solutions. Similarly the slight underprediction of the axial velocity far downstream is likely also due to the slipstream contraction.

The three-dimensional grid was a $53 \times 105 \times 105$ rectangular grid covering the region $x \in [-11.34R, 11.34R]$, $y \in [-10.6R, 10.6R]$, $z \in [-10.6R, 10.6R]$. The nodes were concentrated near the plane of the disk ($x = 0$) and near the its edge ($x^2 + y^2 = R^2$),

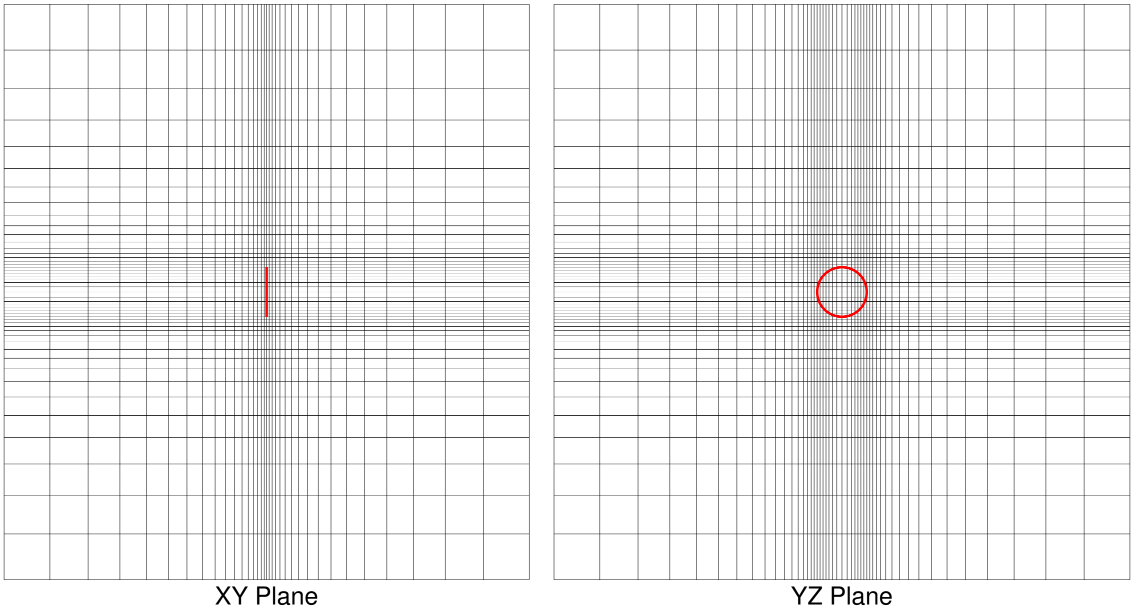

***Figure 6:*** *An example of the node clustering in the three-dimensional grid. The red lines show the location of the actuator disk.*

with the smallest cell dimension being $0.02R$. The half-width of the source density distribution was $\Delta x = 0.1R$. Figure 6 shows a less dense version of the grid to illustrate the concentration of nodes.

This grid was also used to perform ANSYS CFX simulations of the same problem. The momentum source density was introduced into ANSYS CFX using a Command Expression Language formula.

Figures 7 and 8 compare the TRANSOM and ANSYS CFX predictions with the analytic solutions. As with the two-dimensional solutions, the smearing of the momentum distribution has been accounted for in the analytic curves. The agreement between TRANSOM and ANSYS CFX is very good with the TRANSOM curve often difficult to discern because it lies beneath the ANSYS CFX curve. This suggests that the small discrepancies with the analytic solution are due to the discretization and the neglect of wake contraction in the analytic solution rather than any problems with the integration by the solvers.

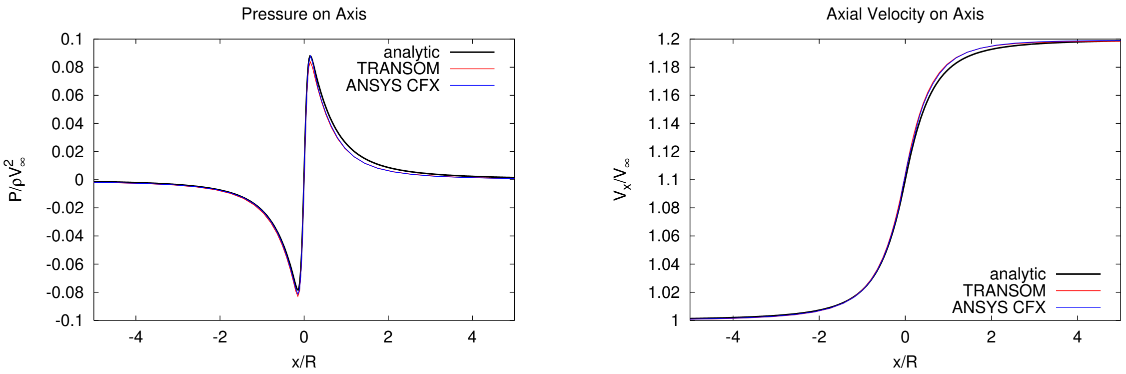

***Figure 7:*** *Comparison of the TRANSOM and ANSYS CFX predictions on a three-dimensional grid with analytic curves for the pressure and axial velocity along the x-axis.*

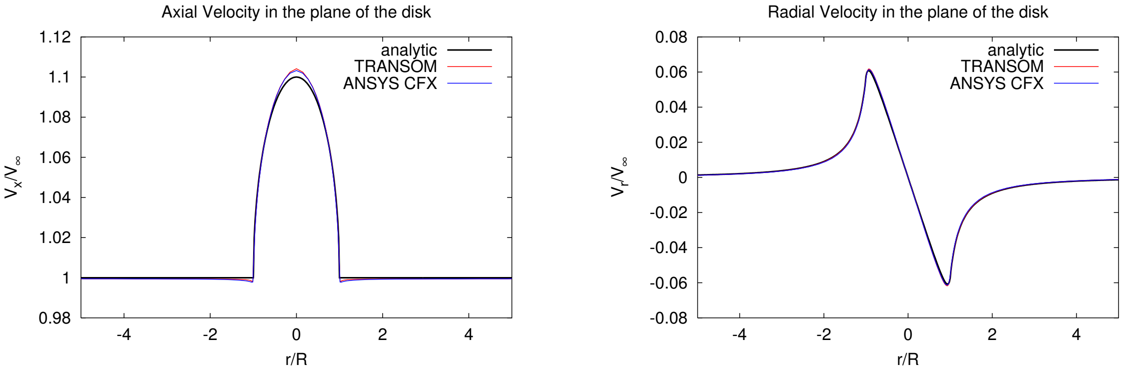

***Figure 8:*** *Comparison of the TRANSOM and ANSYS CFX predictions on a three-dimensional grid with analytic curves for the velocity in the plane* $x = 0$.

# 4 Concluding remarks

The DRDC Atlantic RANS solver TRANSOM has been modified to allow for mass and momentum source terms in the RANS equations. This will allow calculations of a propeller's effective wake by coupling TRANSOM with a propeller panel code such as PROCAL or ASP. The modifications have been validated using three flows for which analytic solutions are available: unidirectional flow with a Gaussian mass source distribution, unidirectional flow with a Gaussian momentum source distribution, and flow through an elliptically loaded actuator disk. The latter flow was also calculated using ANSYS CFX. In all cases the agreement with the analytic solutions was very good.

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In preparation for calculating effective wakes by replacing a propeller with an embedded force field, the DRDC Atlantic flow solver TRANSOM has been modified to allow for mass and momentum source terms in the Reynolds-averaged Navier-Stokes equations. The modifications have been validated using three flows for which analytic solutions are available: unidirectional flow with a Gaussian mass source distribution, unidirectional flow with a Gaussian momentum source distribution, and flow through an elliptically loaded actuator disk. The latter flow was also calculated using ANSYS CFX. In all cases the agreement with the analytic solutions was very good.

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