Appendix A Manufacturer Given Information and Rotor Drawings

The first part of this section includes some given information from manufacturers, mainly for meters A, B and C. The second part collates each rotor drawing that was produced by Solidworks.

A.1 Manufacturer Given Information

A.1.1 Meter A

A drawing is given by the manufacturer, Euromatic, and the image is shown below.

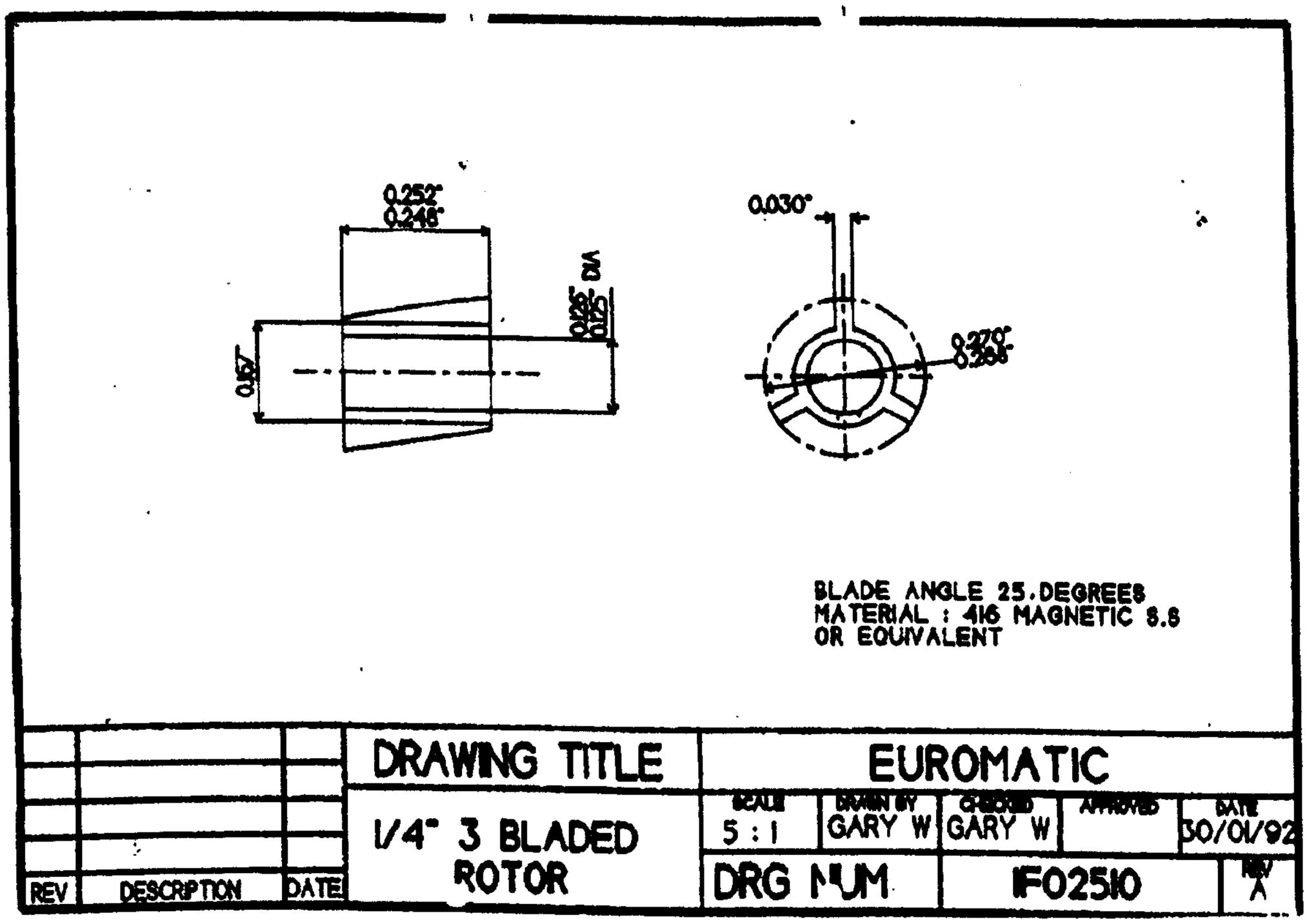


Figure A. 1 **Meter A – Image of the given drawing (note: the "SCALE" is not a true representation due to changed image size)**

Though the meter (rotor casing) nominal diameter is 6 mm, the pipe fitting is actually for 12 mm, therefore the effective pipe diameter is truncated from 12 mm to 6 mm at both ends of the meter body. A photographic view of the front of meter A is presented below showing this feature.

Figure A. 2 Photographic view of the front of meter A

A.1.2 Meter B

A drawing is given by Euromatic and is shown below.

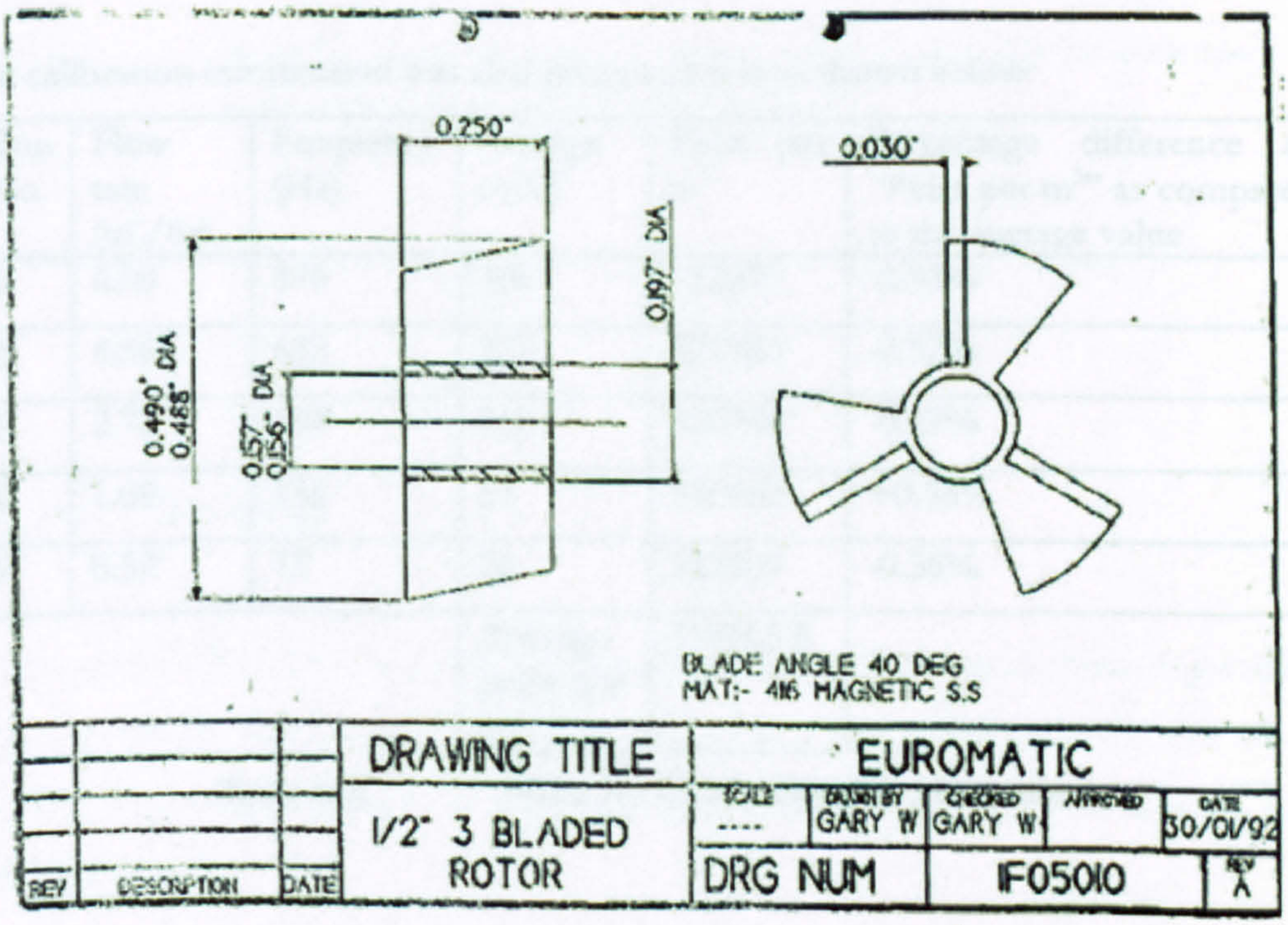


Figure A. 3 Meter B – Image of the given drawing

The manufacturer also provides some details of this meter, such as the materials and bearing type, and they are tabulated in the table below.

1.	Meter type	TB/½/GB
2.	Connection/Size	½" BSP Threaded
3.	Maximum body pressure	350 bar
4.	Body material	Stainless steel 316
5.	Flange material	N/A
6.	Internal support material	Stainless steel 316
7.	Shaft material	Tungsten carbide
8.	Bearing type	Ball race
9.	Rotor type	17/4 PH
10.	Flow range	0.11-1.1 m^3/hr
11.	Calibration units	m^3
12.	Electrical connection	M25
13.	Pick-up type	Magnet and coil
14.	Temperature range	-40°C to +100°C

Table A. 1 Meter B – Given details

Some calibration information was also given and it is as shown below:

Run No.	Flow rate (m^3/hr)	Frequency (Hz)	Voltage (mV)	Pulse per m^3	Percentage difference of "Pulse per m^3" as compared to the average value
1	6.00	870	306	522070	-0.53%
2	4.36	632	222	521980	-0.52%
3	2.72	394	138	520700	-0.27%
4	1.09	156	55	516402	+0.56%
5	0.52	75	26	522209	-0.56%
			Average pulse per m^3:	519305.5	

Table A. 2 Meter B – Given calibration information

A.1.3 Meter C

A drawing is given by Bestobell and an image of this is shown below.

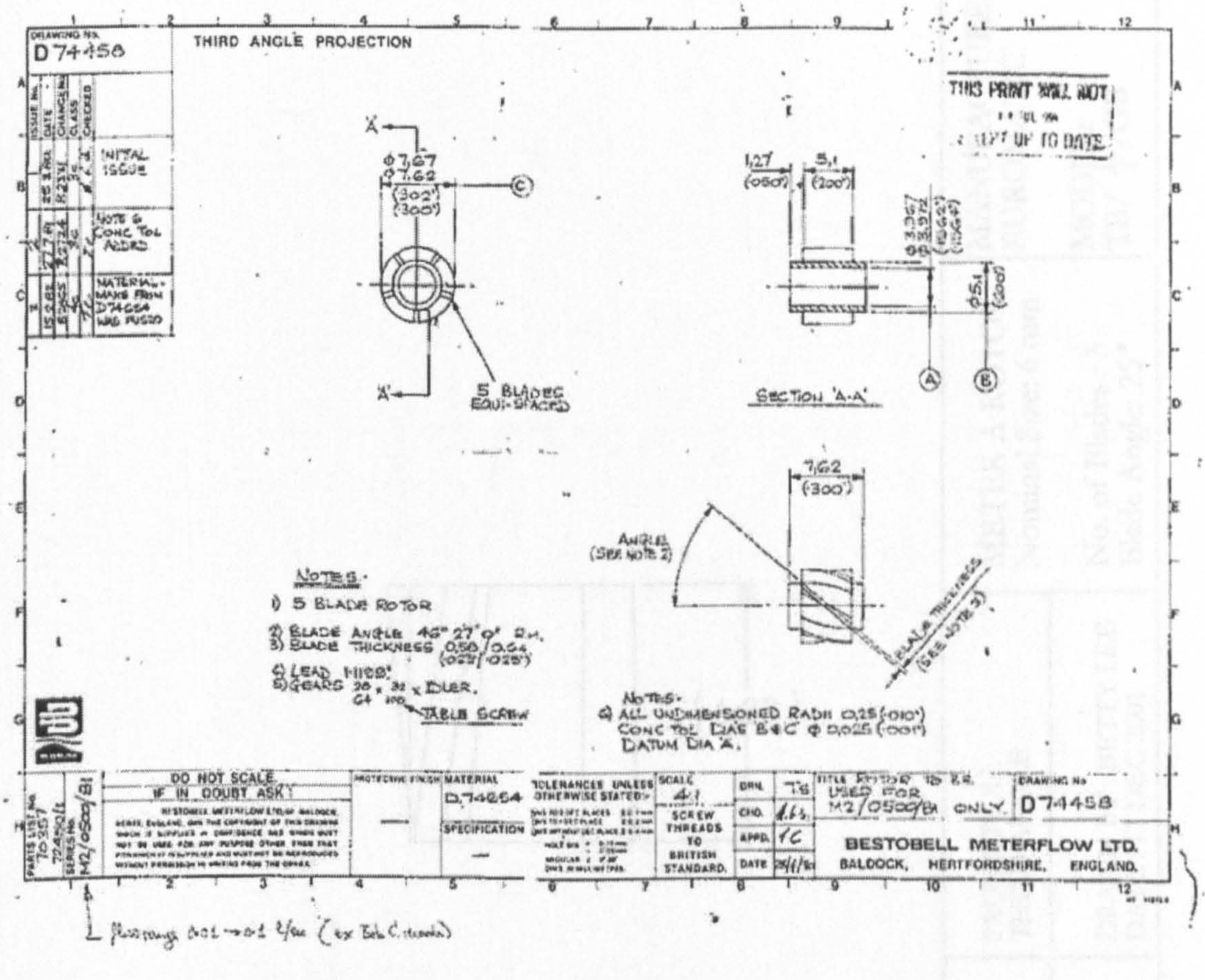


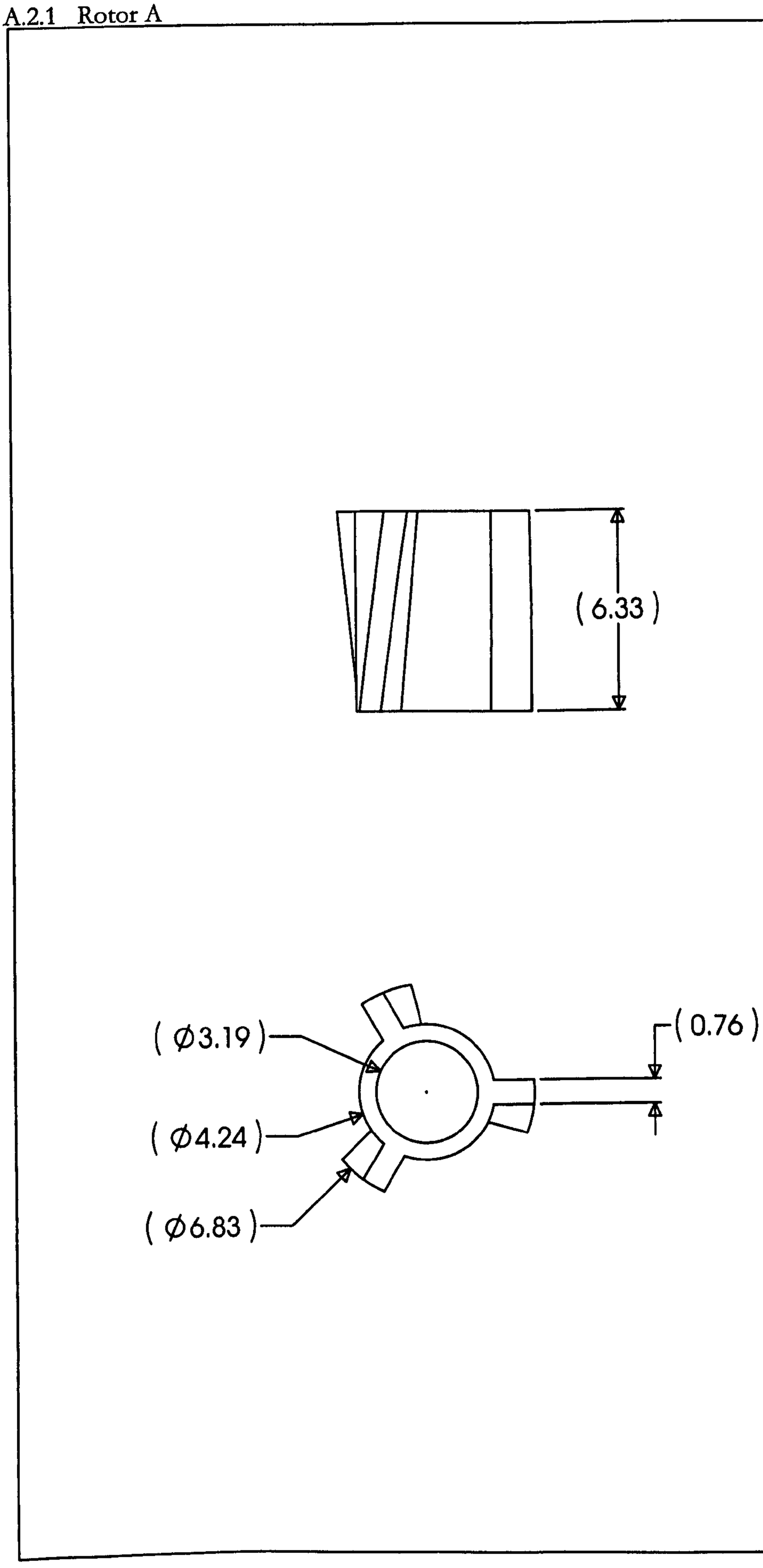
Figure A. 4 **Meter C – Image of the given drawing (note: the "SCALE" is not a true representation due to changed image size)**

Note: No meter information was given by manufacturers for meters D and E.

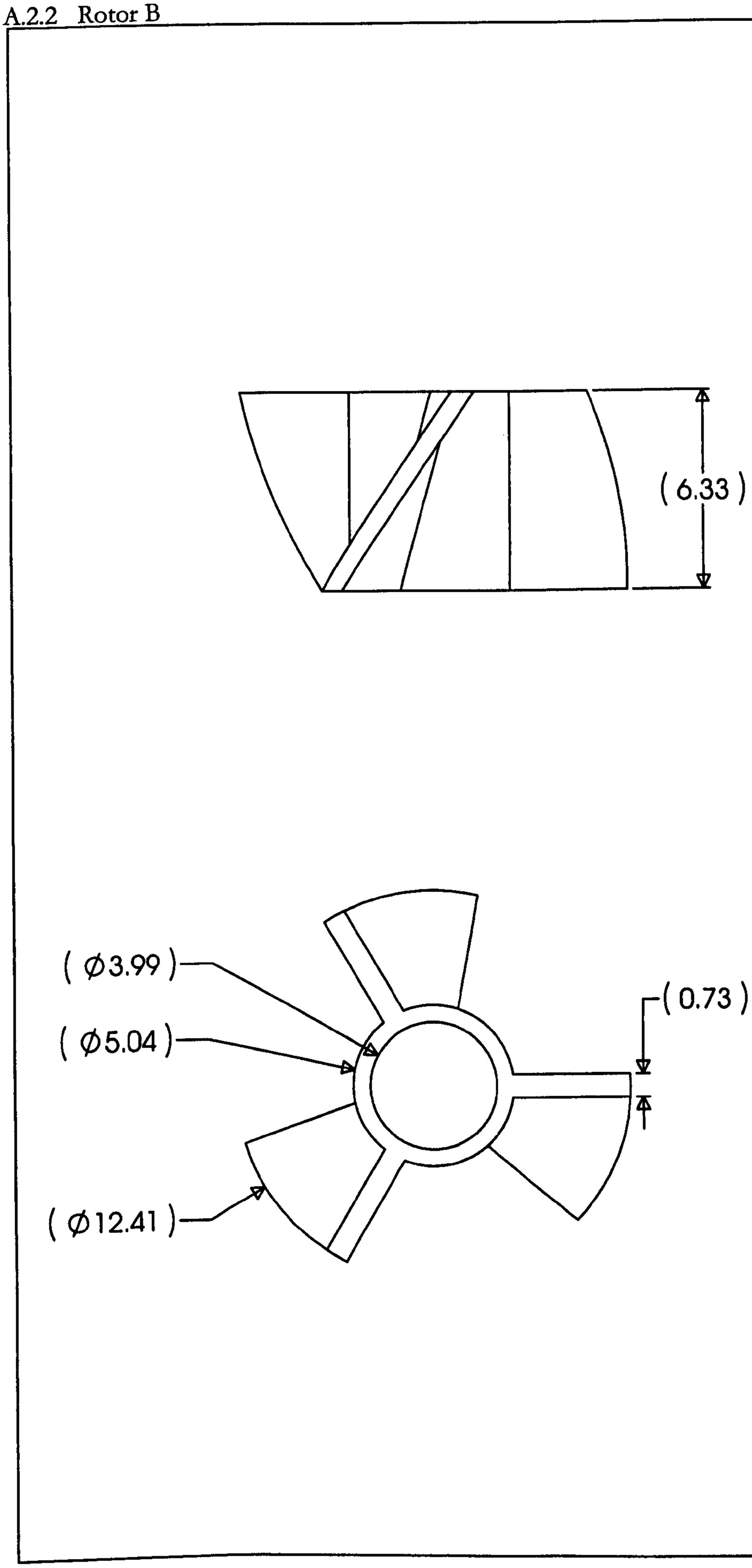
A.2 Rotor Drawings

For the purpose of evaluating rotor inertia and estimating fluid inertia (assuming solid body rotation within the rotor envelope), geometrical information of all rotors in this study are input into Solidworks to allow for this computation and the resulting drawings are collated in this section.

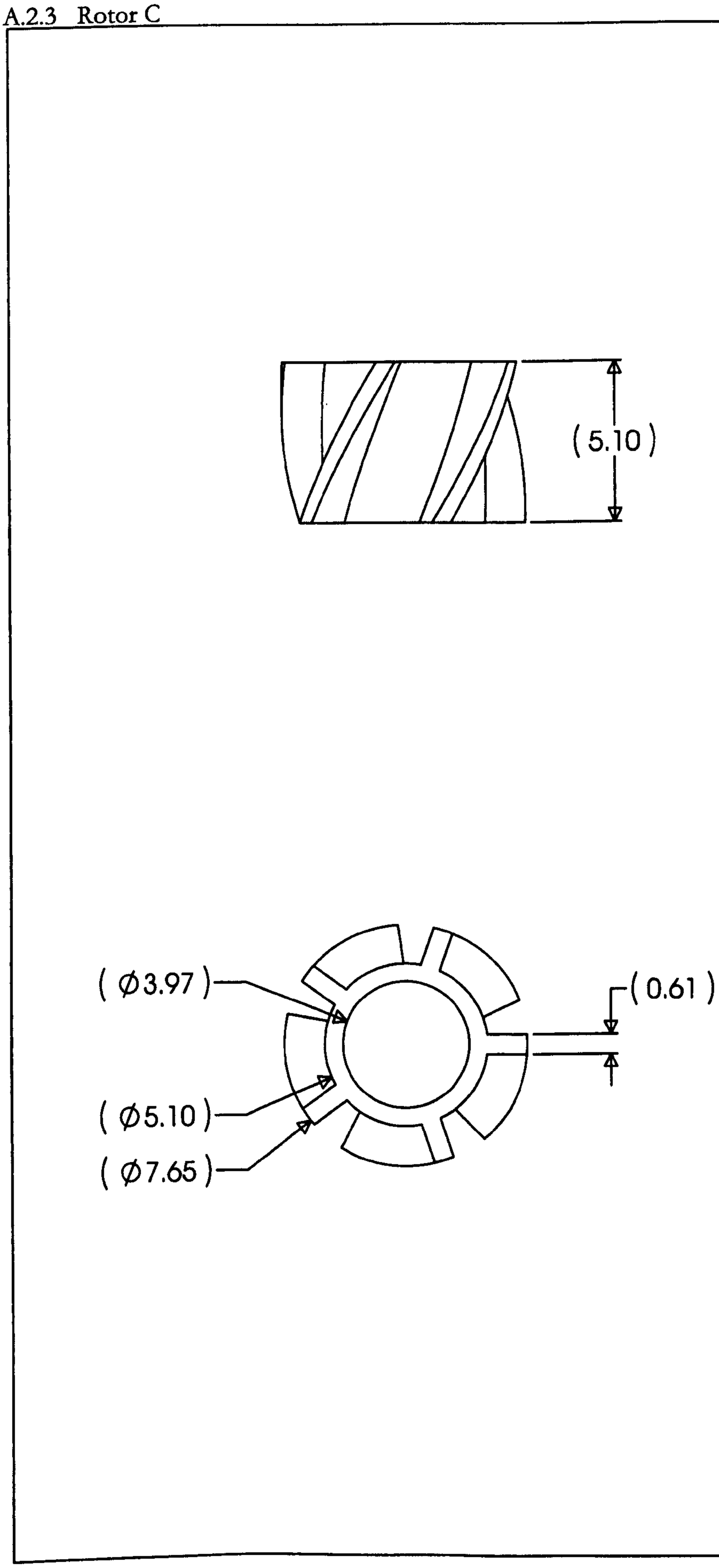
A.2.1 Rotor A


(6.33)
(Ø3.19)
(Ø4.24)
(Ø6.83)
(0.76)
MANUFACTURER: EUROMATIC
MODEL: TB/ 1/4 /GB
METER A ROTOR
Nominal Size: 6 mm
No. of Blades : 3
Blade Angle: 25°
PROJECTION: THIRD ANGLE
DRAWN BY : BETTY LEE
DATE : 17 DEC 2001
SCALE 5 : 1
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN mm
TOLERANCES ARE: ON LINEARS ±0.01 ON ANGLES +1°
SYSTEMS ENG. DEPT.
BRUNEL UNIVERSITY

A.2.2 Rotor B


(6.33)
(Ø3.99)
(Ø5.04)
(Ø12.41)
(0.73)
MANUFACTURER:
EUROMATIC
MODEL:
TB/ 1/2 /GB
METER B ROTOR
Nominal Size: 12 mm
No. of Blades : 3
Blade Angle: 40°Tip
20°Hub
PROJECTION:
THIRD ANGLE
DRAWN BY : BETTY LEE
DATE : 17 DEC 2001
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN mm
TOLERANCES ARE:
ON LINEARS ±0.01
ON ANGLES +1°
SCALE 5 : 1
SYSTEMS ENG. DEPT.
BRUNEL UNIVERSITY

A.2.3 Rotor C



MANUFACTURER: BESTOBELL

MODEL: M2/0500/B1

METER C ROTOR
Nominal Size: 12 mm

No. of Blades : 5
Blade Angle: 46°

PROJECTION: THIRD ANGLE

DRAWN BY : BETTY LEE
DATE : 17 DEC 2001

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN mm

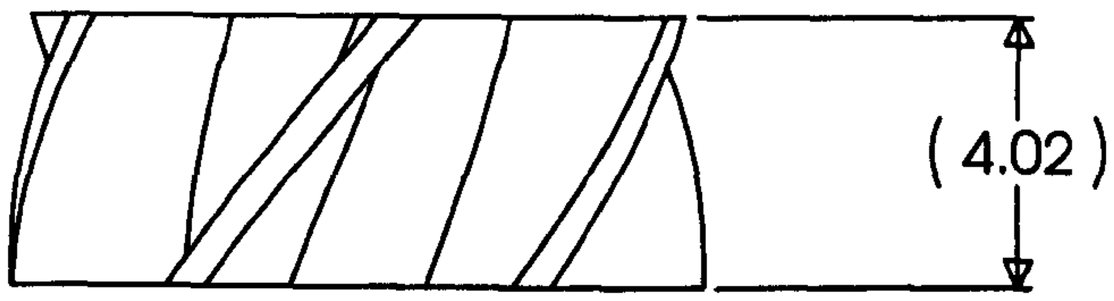
SCALE 5 : 1

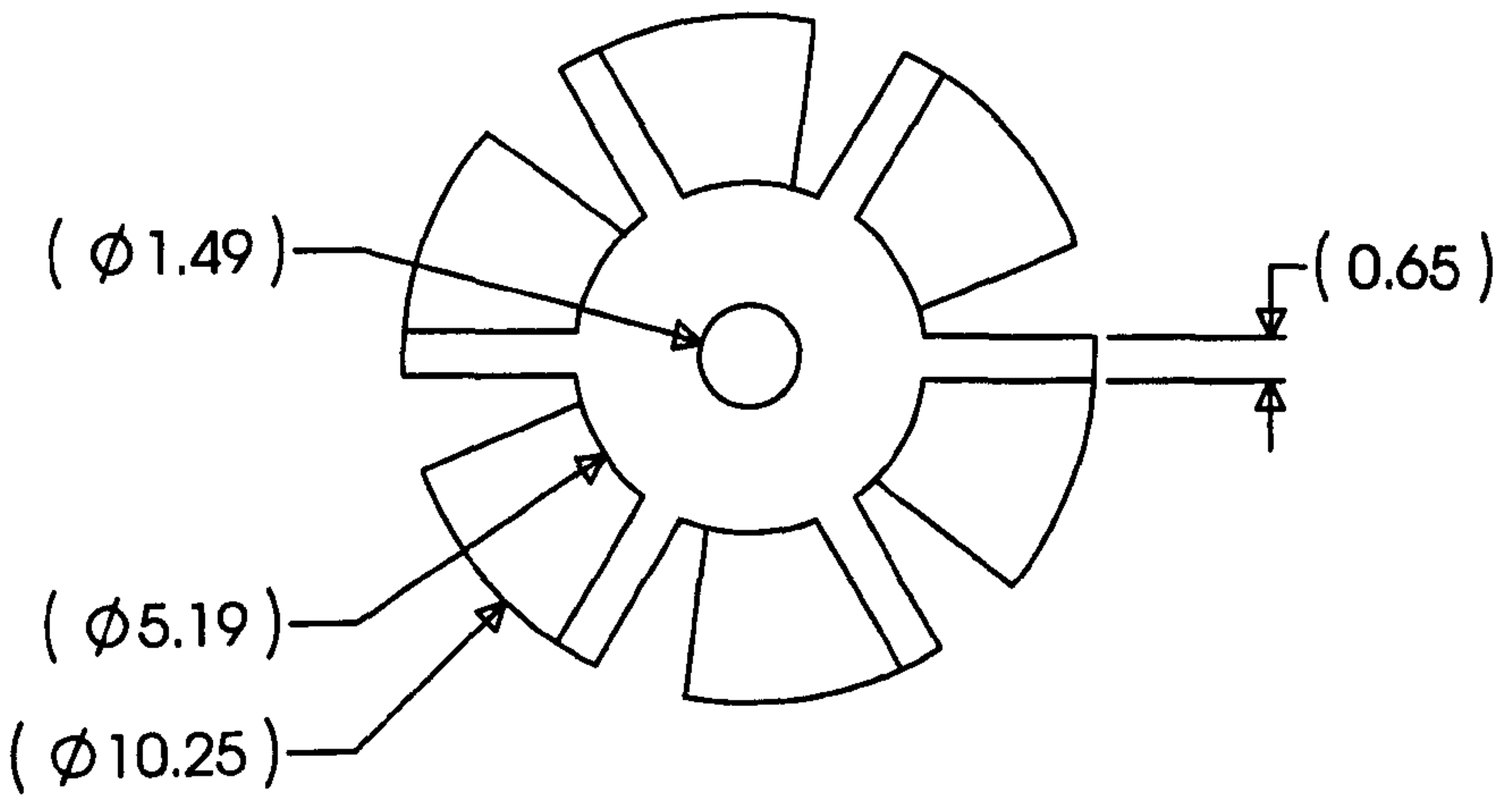
TOLERANCES ARE:
ON LINEARS ±0.01
ON ANGLES +1°

SYSTEMS ENG. DEPT.

BRUNEL UNIVERSITY

A.2.4 Rotor D





MANUFACTURER: BESTOBELL

MODEL: MX1/15/25

METER D ROTOR
Nominal Size: 12 mm

No. of Blades : 6
Shaft not included in the drawing

PROJECTION: THIRD ANGLE

DRAWN BY : BETTY LEE
DATE : 17 DEC 2001

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN mm

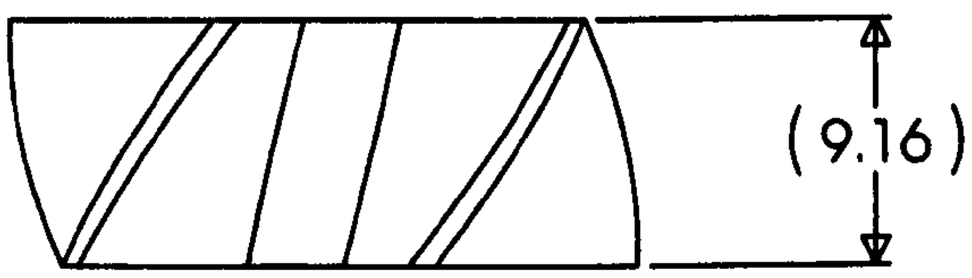
SCALE 5 : 1

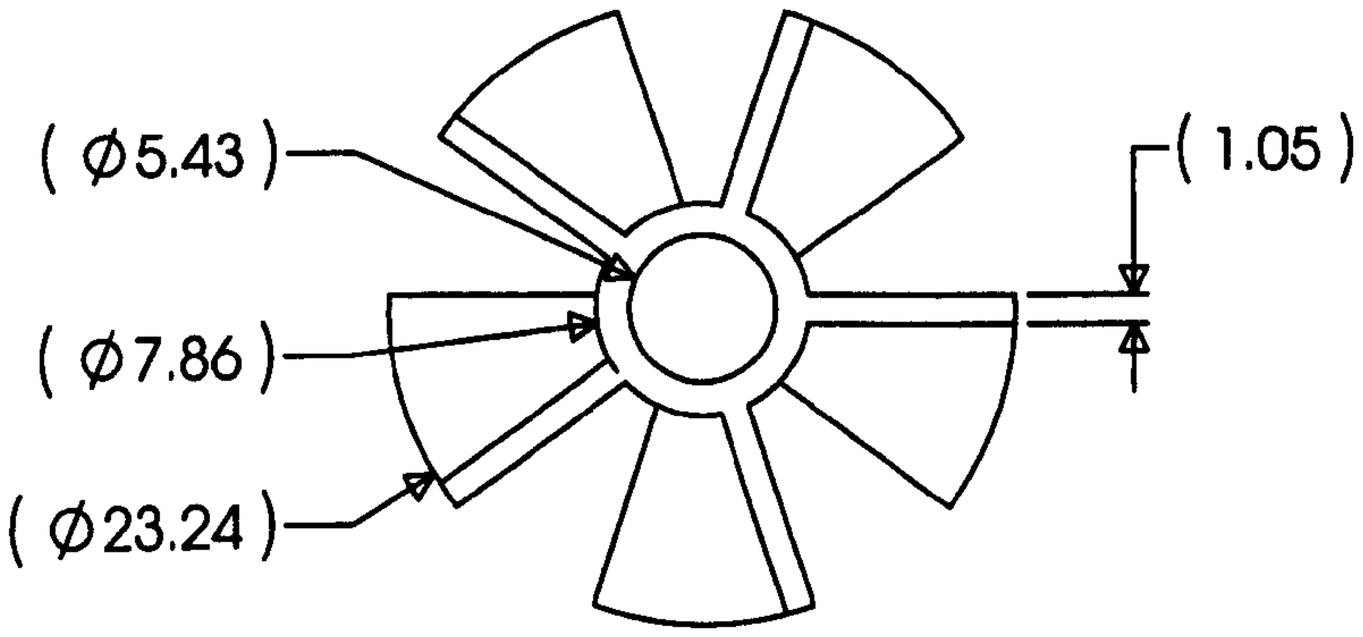
TOLERANCES ARE: ON LINEARS ±0.01 ON ANGLES ±1°

SYSTEMS ENG. DEPT.

BRUNEL UNIVERSITY

A.2.5 Rotor E





MANUFACTURER: ATS

MODEL: B/1/6D

METER E ROTOR
Nominal Size: 25 mm

No. of Blades : 5

PROJECTION: THIRD ANGLE

DRAWN BY : BETTY LEE
DATE : 17 DEC 2001

SCALE 2 : 1

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN mm

TOLERANCES ARE:
ON LINEARS ±0.01
ON ANGLES +1°

SYSTEMS ENG. DEPT.

BRUNEL UNIVERSITY

Appendix B Step Response Test Method

The step response test results (described in Chapter 7.2.1) were obtained by using the method described by Cheesewright and Clark (1997). As extracted from their paper (Section 3 "Apparatus for step test experiments"), this section describes the test method which is of particular relevance to this study.

"The values of the time constant required that for changes in flow to be considered as step changes would take place over a period of the order of 1 ms. Since the mean velocity of flow through a typical small turbine meter is several meters per second, it was apparent that the dynamic pressure forces could be very large. It was therefore decided that any mechanism controlling the flow would have to be immediately downstream of the meter and that the supply to the meter would have to be via a pipe having a diameter significantly greater than that of the meter. The flow was provided by a blow-down system, driven by compressed air, and the available pressure vessel limited the maximum pressure to 3.5 bar."

"Figure B.1 shows a schematic representation of the apparatus and Fig B.2 shows details of the variable-area orifice that controlled the flow. The rapid change of flow was achieved by driving the variable width slot across the circular orifice with a spring-loaded plunger device. Some control of the speed of change could be achieved by varying the energy with which the plunger impacted the slot (by varying the amount of compression imposed on the plunger spring). The linear movement of the slot which was necessary to go from one effective flow area to the other was approximately 10mm and overshoot was prevented by the use of a stop which was made magnetic to avoid the possibility of rebound."

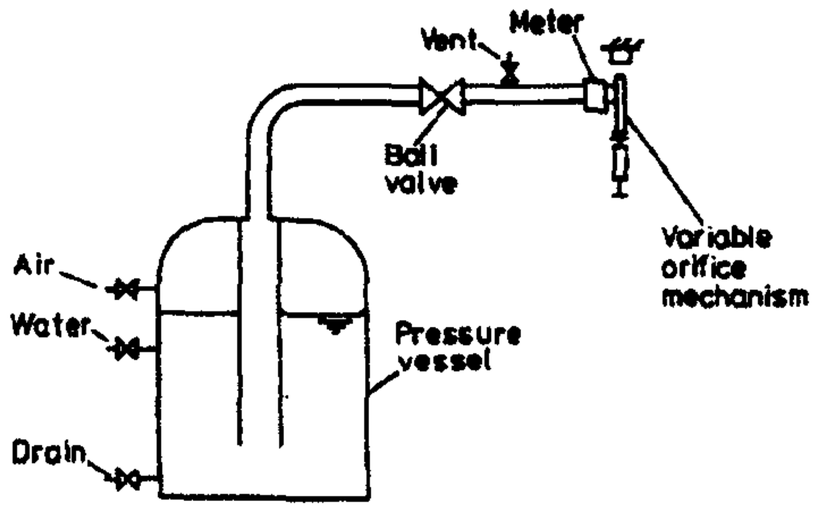


Figure B. 1 **Schematic representation of the apparatus for step tests**

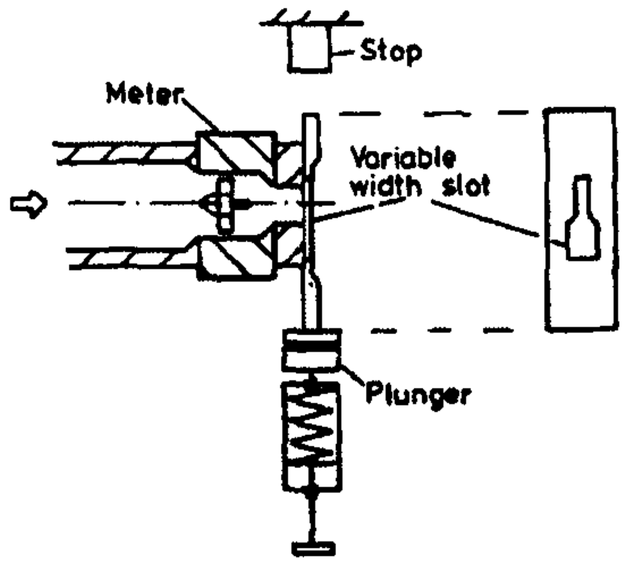


Figure B. 2 **Details of the variable-area orifice used to produced changes in the flow**

"Estimates of the velocity with which the variable width slot moved across the orifice suggested that the change of flow area could be achieved in less than 1ms. Estimates of the dynamic pressure forces available in the flow confirmed that the required changes in flowrate (positive and negative) could be produced within this period. Some confirmation of these estimates was obtained from the fact that when the velocity of the slot was reduced by a factor of approximately 2, no significant change could be detected in the small step response of a given meter."

"It is known that the details of a flow, more than five orifice diameters upstream of an orifice, are not affected by details of the orifice and in all cases the turbine was further than this away from the variable orifice (note that Fig. B.2 is schematic and is not to scale). It is therefore believed that there was no significant upstream influence on the turbine during the 'small step' response tests."

The same data acquisition programs built in Labview, as described in Chapter 6.1.3, were used here for obtaining turbine meter raw data; and the same data processing technique (described in Chapter 6.3) was used to process the subsequent meter data.

Appendix C The Flow Model

CFX provides a solution module that solves the discretised representation of the problem. A detailed description of the software is given in the Manual. This section is intended to describe the fundamental mathematical formulations and methods used to depict the flow behaviour, rather than as a full text. Where appropriate, the equations and their underlying assumptions are presented in full. In cases where the full equations have been omitted, references are presented where the analysis and derivations can be found.

C.1 Governing Equations

The foundation of computational fluid dynamics (CFD) is the fundamental governing equations of fluid dynamics — the continuity, momentum and energy equations. Since the fluid flow modelled in this study is assumed to be isothermal, the energy equation is therefore not considered.

C.1.1 Continuity equation

The CFX flow solver provides numerical solutions to the Reynolds' averaged Navier Stokes equations. For an elemental control volume, there is a balance between the mass flow rates entering and leaving per unit time and the rate of change in density. This may be expressed in symbolic notation form as (Fox and McDonald 1994):

$$\underbrace{\frac{\partial \rho}{\partial t}}_{\text{local derivative}} + \underbrace{\nabla \cdot (\rho U)}_{\text{convective derivative}} = 0 \qquad \textbf{Eq. C. 1}$$

Where: ρ is density;

t is time;

U is velocity; and

$\nabla \cdot (\rho U)$ is called the divergence of the velocity, it is physically the time rate of change of the volume of a moving fluid element, per unit volume (Anderson, Jr. 1992).

Eq. C. 1 suggests that an elemental control volume in a flow field may undergo change in mass flow rate for either of two reasons. It may be changed because it is "convected" into a region of higher (or lower) mass flow rate. If the fluid is compressible, the elemental control volume will undergo an additional "local" change in mass, and it is a function of time (Fox and McDonald 1994). For a flow of constant density, i.e. incompressible, this equation reduces to:

$$\nabla \cdot \boldsymbol{U} = 0 \qquad \textbf{Eq. C. 2}$$

C.1.2 Navier-Stokes Equations

Both laminar and turbulent flow may be described by the Navier-Stokes equations, which were developed by considering the forces acting on an elemental parallelepiped in the fluid.

The conservation of momentum equation describes the equilibrium between surface forces, body forces and inertia forces for an element of fluid in the flow. Surface forces are a combination of pressure forces, which act normal to the principal axes, and viscous forces, which act as shear forces on the faces of the fluid element. Body forces are forces developed without physical contact, and distributed over the volume of fluid (Fox and Mc Donald 1994). Gravitational force, centrifugal force, Coriolis force and electromagnetic force are examples of body forces. Inertia forces are the products of the mass and acceleration of the fluid element. The change in velocity of this element is brought about both by the movement of position and by the progress of time (Nakayama and Boucher 1999).

The equations can be written symbolically in the format as (Stanley Middleman 1998):

$$\underbrace{\rho\left[\frac{D\boldsymbol{U}}{Dt}\right]}_{\text{inertia term}} = \underbrace{\boldsymbol{B}}_{\text{body force term}} - \underbrace{\nabla p}_{\text{pressure term}} + \underbrace{\mu\left[\nabla^2 \boldsymbol{U}\right]}_{\text{viscous term}} \qquad \textbf{Eq. C. 3}$$

Where: $\boldsymbol{B}$ is body force;

p is pressure;

μ is dynamic viscosity.

All other symbols are as before.

The Navier-Stokes equations can also be represented in coordinates form. In cylindrical coordinates for constant density and viscosity, they are:

$$\rho\left(\frac{\partial u_x}{\partial t}+u_r\frac{\partial u_x}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_x}{\partial \theta}+u_x\frac{\partial u_x}{\partial x}\right)=$$

$$\rho g_x-\frac{\partial p}{\partial x}+\mu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_x}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u_x}{\partial \theta^2}+\frac{\partial^2 u_x}{\partial x^2}\right\} \qquad \textbf{Eq. C. 3a}$$

$$\rho\left(\frac{\partial u_r}{\partial t}+u_r\frac{\partial u_r}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_r}{\partial \theta}-\frac{{u_\theta}^2}{r}+u_x\frac{\partial u_r}{\partial x}\right)=$$

$$\rho g_r-\frac{\partial p}{\partial r}+\mu\left\{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}[ru_r]\right)+\frac{1}{r^2}\frac{\partial^2 u_r}{\partial \theta^2}-\frac{2}{r^2}\frac{\partial u_\theta}{\partial \theta}+\frac{\partial^2 u_r}{\partial x^2}\right\} \qquad \textbf{Eq. C. 3b}$$

$$\rho\left(\frac{\partial u_\theta}{\partial t}+\frac{1}{r}[ru_r]\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial \theta}+\frac{u_r u_\theta}{r}+u_x\frac{\partial u_\theta}{\partial x}\right)=$$

$$\rho g_\theta-\frac{1}{r}\frac{\partial p}{\partial \theta}+\mu\left\{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}[ru_\theta]\right)+\frac{1}{r^2}\frac{\partial^2 u_\theta}{\partial \theta^2}-\frac{2}{r^2}\frac{\partial u_r}{\partial \theta}+\frac{\partial^2 u_\theta}{\partial x^2}\right\} \qquad \textbf{Eq. C. 3c}$$

Where: x, r, θ are the three unit directions along the principal axes;

u_x, u_r, u_θ are the three components of velocity along the principal axes; and

g_x, g_r, g_θ are the three components of body force term along the principal axes.

All other symbols are as before.

C.2 Turbulence Models

The continuity equation and the Navier-Stokes equations described in section C.1 provide a full description of the isothermal and incompressible Newtonian flow behaviour of a fluid element in laminar flow. However, turbulent flows are extremely complex and time-dependent; since the Navier-Stokes equations are non-linear, coupled and contains partial differential, it is difficult to solve them to the required accuracy analytically, therefore turbulence models are used, which solve transport equations for the Reynolds-averaged quantities.

Variables in the flow equations are split into mean and fluctuating parts. The transport equations are then solved for the mean quantities, and turbulence models are used to approximate the fluctuating parts. For example, under unsteady flow condition, the velocity is written as the sum of the phase mean velocity and the fluctuating velocity:

$$U = \overline{U} + \left(\langle \overline{U} \rangle - \overline{U}\right) + U' = \langle \overline{U} \rangle + U' \qquad \textbf{Eq. C. 4}$$

Where: $\overline{U}$ is mean velocity;

$\langle \overline{U} \rangle$ is phase mean velocity (only exists under unsteady flow condition);

U' is fluctuating velocity.

Taking the average of each term, except for the cross-products of the fluctuating velocities, the phase mean Reynolds averaged Navier-Stokes equation in symbolic form is given by:

$$\rho\left[\frac{D\langle \overline{U} \rangle}{Dt}\right] = \langle \overline{B} \rangle - [\nabla \langle \overline{p} \rangle] + \mu[\nabla^2 \langle \overline{U} \rangle] - \rho[\nabla \langle \overline{U'U'} \rangle] \qquad \textbf{Eq. C. 5}$$

The extra term, $\rho[\nabla \langle \overline{U'U'} \rangle]$, is due to the velocity fluctuations, is called the Reynolds stresses. These terms arise from the non-linear convective term in the unaveraged equations. These components can be regarded as expressions for the transport of a fluctuating momentum by turbulent velocity fluctuations (Abbott and Basco 1994).

Turbulence models close the continuity and Reynolds averaged Navier-Stokes equations by providing models for the computation of the Reynolds stresses. The models that the

solver provides can be put into two broad classes: eddy viscosity models and second order closure models.

Eddy viscosity models solve the Reynolds stresses and fluxes algebraically in terms of known mean quantities. The eddy viscosity hypothesis is that the Reynolds stresses can be linearly related to the mean velocity gradients in a manner analogous to the relationship between the stress and strain tensors in laminar Newtonian flow. These models are distinguished by the manner in which they prescribe the eddy viscosity and eddy diffusivity. Examples are k-ε model, low Reynolds number k-ε model and RNG k-ε model. The low Reynolds number model is the modification of the standard models to allow calculation of turbulent flows at low Reynolds number, typically in the range 5,000 to 30,000. Since we aim to solve to the laminar boundary layer of blade surfaces in which the local Reynolds number is around 20,000 (see section C.3.3), therefore low Reynolds number k-ε model was chosen to be the prime model for this research case.

Second order closure models solve differential transport models for the turbulent fluxes, which have to be modelled in terms of known lower order ones. These types of models are often called Reynolds stress models. The advantage of doing this over the methods mentioned previously is that those methods give a single additional viscosity, whereas the direct modelling of the stress terms allows the effects of turbulence to vary in the three coordinate directions. Eddy viscosity models are said to give isotropic turbulence, in which turbulence is assumed to be constant in all directions, whereas in the real situation the turbulence is said to be anisotropic (Shaw 1992). However, low Reynolds number versions of these models were not available within the solver. Therefore, no further description of these models will be presented here.

C.2.1 Eddy viscosity models

The Reynolds stresses are assumed directly proportional to the mean velocity gradients, with the constant of proportionality being the turbulent viscosity, for example, in cylindrical coordinates:

$$-\overline{u_r' u_\theta'} = \frac{\mu_t}{\rho}\left(r\frac{\partial}{\partial r}\frac{u_\theta}{r} + \frac{1}{r}\frac{\partial u_r}{\partial \theta}\right) \qquad \textbf{Eq. C. 6}$$

Where: μ_t is the turbulent viscosity;

r, θ are the unit directions along the principal axes;

u_r, u_θ are the components of velocity along the principal axes;

u'_r, u'_θ are the components of fluctuating velocity.

All other symbols are as before.

The turbulent viscosity is not a value of a physical property dependent on the temperature or such, but a quantity fluctuating according to the flow condition (Nakayama and Boucher 1999):

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \qquad \textbf{Eq. C. 7}$$

where: C_μ is a constant;

k is the turbulent kinetic energy (note it has units of velocity squared);

ε is the rate of dissipation of turbulent kinetic energy

Turbulent transport will have a substantial effect on boundary layer development within a turbine flowmeter. CFX 4.3 incorporates a range of models for turbulent transport suitable for use in engineering calculations. A brief summary of three of the available turbulence models, which were considered in preliminary investigations, is presented below.

C.2.1.1 k-ε model

The standard k-ε model (Launder and Spalding 1974) uses an eddy-viscosity hypothesis for the turbulence. In addition to the mean flow equations, it solves separate transport equations for both turbulent kinetic energy, k, and the rate of dissipation of turbulent kinetic energy, ε for use in Eq. C. 7 to determine μ_t. At any point in the flow this same μ_t is used in all flow directions, i.e. for all Reynolds stress components. This usage is equivalent to the assumption of a local isotropy in the turbulence (Abbott and Basco 1994). Both equations have the same form; the rate of change of k or ε is related to the convective and diffusive transport and the production and dissipation. Resorting to vector notation, the equations are written as:

$$\rho\frac{\partial k}{\partial t}+\nabla\cdot(\rho \boldsymbol{U} k)=P+\boldsymbol{B}-\rho\varepsilon+\nabla\cdot\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\nabla k\right) \qquad \textbf{Eq. C. 8}$$

$$\rho\frac{\partial \varepsilon}{\partial t}+\nabla\cdot(\rho \boldsymbol{U}\varepsilon)=C_1\frac{\varepsilon}{k}(P+C_3\boldsymbol{B})-C_2\rho\frac{\varepsilon^2}{k}+\nabla\cdot\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right) \qquad \textbf{Eq. C. 9}$$

Where: C_1, C_2, σ_k, σ_ε are model constants,

P is the shear production, defined below

All other symbols are as before.

$$P=(\mu+\mu_t)\nabla \boldsymbol{U}\cdot\left(\nabla \boldsymbol{U}+(\nabla \boldsymbol{U})^T\right)-\frac{2}{3}\nabla \boldsymbol{U}((\mu+\mu_t)\nabla \boldsymbol{U}+\rho k) \qquad \textbf{Eq. C. 10}$$

The constants in these equations have been developed following studies of a wide range of turbulent flows.

This model is not suitable for solution in the near wall region of a boundary layer. Where such a solution is required the model may be used in combination with a wall function to bridge the near wall region calculation.

C.2.1.2 Low Reynolds number k-ε model

CFX Flow Solver provides this particular turbulent model developed by Launder and Sharma (1974), it is a modification of the standard k-ε model to allow calculation of turbulent flows at low Reynolds number, typically in the range 5000 to 30000. The model involves a damping of the turbulent viscosity when the local turbulent Reynolds number is low, a modified definition of ε so that it goes to zero at walls and modifications of the source terms in the ε equation. The equations are integrated to the wall through the laminar sublayer.

Practically all incompressible turbulence models invoke the large Reynolds number (Re) assumption, thus allowing the effects of viscosity to be neglected as a first approximation. This assumption has its drawback as the flow Re decreases or as a wall is approached. In

both cases, the effective Re of the flow becomes smaller. However, there is a distinct difference between the two situations even though the effective flow Re is the same. For flows in an infinite medium, there are no walls and decreasing Re introduces viscous effects only. On the other hand, the local Re decreases as a wall is approached and, in addition, the wall reflects the fluctuating pressure and thus contributes to an increased anisotropy of the turbulence field near the wall. This effect is commonly known as wall blocking. Therefore, near-wall turbulence includes both viscous and blocking effects while low-Re turbulence consists of viscous effects alone (Speziale and So 1998).

The equations describing the turbulence model: Eq. C. 7, Eq. C. 8 and Eq. C. 9 become:

$$\mu_t = C_\mu f_\mu \rho \frac{k^2}{\varepsilon} \qquad \textbf{Eq. C. 11}$$

$$\rho\frac{\partial k}{\partial t} + \nabla\cdot(\rho \boldsymbol{U} k) = P + \boldsymbol{B} - \rho\varepsilon + \nabla\cdot\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right) - D \qquad \textbf{Eq. C. 12}$$

$$\rho\frac{\partial \varepsilon}{\partial t} + \nabla\cdot(\rho \boldsymbol{U} \varepsilon) = C_1\frac{\varepsilon}{k}(P + C_3\boldsymbol{B}) - C_2 f_2 \rho\frac{\varepsilon^2}{k} + \nabla\cdot\left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right) + E \qquad \textbf{Eq. C. 13}$$

Here the definition of P is changed slightly from Eq. C. 10 to use μ_t only instead of $(\mu+\mu_t)$.

The functions f_μ, f_2, D and E are defined by:

$$f_\mu = \exp\left(\frac{-3.4}{1+(R_T/50)^2}\right) \qquad \textbf{Eq. C. 14}$$

$$f_2 = 1 - 0.3\exp\left(-R_T{}^2\right) \qquad \textbf{Eq. C. 15}$$

$$D = 2\mu\left(\nabla k^{1/2}\right)^2 \qquad \textbf{Eq. C. 16}$$

$$E = 2\frac{\mu\mu_t}{\rho}(\nabla\nabla \boldsymbol{U})^2 \qquad \textbf{Eq. C. 17}$$

where the local turbulent Reynolds number is defined by:

$$R_T = \frac{\rho k^2}{\mu\varepsilon} \qquad \textbf{Eq. C. 18}$$

C.2.1.3 RNG k-ε model

RNG k-ε model is an alternative to the standard k-ε model for high Reynolds number flows. It derives from a renormalization group analysis of the Navier-Stokes equations and differs from the standard model only through a modification to the equation for ε, except for using a different set of model constants.

The RNG model has not been as widely validated as the k-ε model. However, it has been shown to give better results for many flow regimes, particularly the highly turbulent flows common in wind engineering applications. According to Caffrey et al (1997), the RNG model can give superior results for swirling flows.

Summary:

In the present study, negligible swirling flow is assumed due to the effect of upstream and downstream flow straighteners. And the interest only lies on solving the hydrodynamic forces acting on the localised region of the rotor blading when the meter is subjected to pulsating flow conditions. This implies that the blade wall boundary layer flow simulation is of most importance. In view of this, as the local Reynolds number of the blade, Re_l is around 20000 within the flow regime (See C.3.3), Low Re number k-ε model was chosen to be the turbulent model for this particular flow problem.

C.3 Mathematical Details on Boundary Conditions

C.3.1 Inlet Boundary

Assuming that the whole volume flow goes through the annular flow passage, the inlet velocity (freestream) can simply be inferred from the following formula:

$$\text{Inlet Velocity} = \text{Volume Flowrate} \div \text{Annular Cross-section Area}$$

$$U_\infty = \dot{V} \div A \qquad \textbf{Eq. C. 19}$$

The value of inlet velocity is calculated based on the experimental flow condition, in which the mean flowrate is 0.292×10^{-3} m^3/s for this meter (See Chapter 6). Knowing the values of the casing radius (r_c) and hub radius (r_h), the annular area is calculated by using the following equation:

$$\begin{aligned} A &= \pi\left(r_c^{\,2} - r_h^{\,2}\right) \qquad \textbf{Eq. C. 20} \\ &= \pi\left[\left(1.293\times10^{-2}\right)^2 - \left(5.04\times10^{-3}\right)^2\right] \\ &= 1.113\times10^{-4}\,\text{m}^2 \end{aligned}$$

Now, by using Eq. C. 19, the inlet freestream mean velocity is:

$$\begin{aligned} \overline{U_\infty} &= 0.292\times10^{-3}\,\text{m}^3/\text{s} \div 1.113\times10^{-4}\,\text{m}^2 \\ &= \underline{2.629\ \text{m/s}} \end{aligned}$$

For steady flow condition, the above value is input into the solver. For unsteady flow condition, pure sinusoidal pulsating flow is assumed. With α_p being the relative pulsation amplitude and f_p being the pulsation frequency, the velocity will be time dependent periodically as follows:

$$U_\infty(t) = \overline{U_\infty}\left(1 + \alpha_p \sin 2\pi f_p t\right) \qquad \textbf{Eq. C. 21}$$

The above equation is then input into Fortran subroutine, USRBCS, for the calculation of boundary condition at the inlet for unsteady flow runs.

The values of the inlet turbulence quantities are based upon the characteristic of a fully developed pipe flow. The equations for the inlet values of turbulent kinetic energy, k, is:

$$k \approx 2u_\tau^2 \qquad \textbf{Eq. C. 22}$$

where u_τ is the shear stress velocity, $\left(=\sqrt{\tau_w/\rho}\right)$, in which τ_w is the wall shear stress.

Introducing a dimensionless skin-friction coefficient, C_f:

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho\overline{U_\infty}^2} \qquad \textbf{Eq. C. 23}$$

$$\therefore u_\tau = \left(\sqrt{C_f/2}\right)\overline{U_\infty} \qquad \textbf{Eq. C. 24}$$

According to Blausius' approximate solution for laminar flow over flat plate using sinusoidal velocity profile, the skin-friction coefficient, $C_f = 0.664(\mathrm{Re}_l)^{-1/2}$ (Massey 1992). Taking the local Reynolds number. to be equivalent to the pipe Reynolds number, for this flow condition, $\mathrm{Re}_l = \mathrm{Re}_d = 3.11\times10^4$, hence $Cf = 3.765\times10^{-3}$. By substituting this value into Eq. C. 24, u_τ is equal to 0.115 and hence k is approximated to be 0.026 m^2/s^2.

The rate of dissipation of turbulent kinetic energy, ε, are

$$\varepsilon = \frac{k^{1.5}}{0.3D} \qquad \textbf{Eq. C. 25}$$

D is the hydraulic diameter of the domain, which is approximated to 0.0125m.

C.3.2 Outlet Boundary

According to Wisler 1998, in order to determine radial variations in vector diagrams and flow properties, it is critical that the pressure gradients, momentum changes, and blade forces on the fluid be balanced in the radial direction. The radial equilibrium equation is formulated from the momentum equation (Eq. C. 3b) for the r component of velocity as shown below. The assumption of axial symmetry has eliminated terms containing variations in the tangential direction θ.

$$\underbrace{\frac{1}{\rho}\frac{\partial p}{\partial r}}_{\text{pressure gradient}} = \underbrace{\frac{u_\theta^{\,2}}{r}}_{\text{centrifugal force}} - \underbrace{u_x \frac{\partial u_r}{\partial x}}_{\text{streamline curvature}} - \underbrace{u_r \frac{\partial u_r}{\partial r}}_{\text{linear accel. in radial dir.}} + \underbrace{f_r}_{\text{radial blade force on fluid}} \qquad \textbf{Eq. C. 26}$$

By assuming that this term can be expressed as a function of radius, and if the streamline curvature term, the linear acceleration term and the blade force term are all equal to zero at the outlet, then a simplified form of the radial equilibrium equation can be written as:

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = \frac{u_\theta^{\,2}}{r} \qquad \textbf{Eq. C. 27}$$

In the circumferential direction, the velocity in the absolute frame is:

$$[u_\theta]_{\text{abs.}} = [u_\theta]_{\text{rel.}} + r\omega \qquad \textbf{Eq. C. 28}$$

Since u_θ only varies with radius, the mean velocity for each radius is then calculated by the following formula:

$$\overline{[u_\theta]}_{\text{abs.}} = \frac{\oint_r ([u_\theta]_{\text{abs.}} \times dv)}{\oint_r dv} \qquad \textbf{Eq. C. 29}$$

where dv is the elemental volume.

Assuming that the datum is on the hub surface, in which the pressure, p_{hub}, is:

$$p_{hub} = \rho \overline{[u_\theta]}^2_{\text{abs.}} \qquad \textbf{Eq. C. 30}$$

Then the pressure can be found for each radial position as follows:

$$p_r = p_{r-1} + \frac{\rho \overline{[u_\theta]}^2_{\text{abs.}} \times dr}{r} \qquad \textbf{Eq. C. 31}$$

This equation is then input into Fortran subroutine, USRBCS, for the calculation of boundary condition at the outlet.

C.3.3 Wall Boundaries

As an illustration, this section shows the procedure in establishing the value of *d*, distance between the wall and centre of the first grid, of the blade wall surrounding grid.

Firstly, the boundary layer characteristic has to be known. The local Reynolds number, Re_l, of the blade is:

$$Re_l = \frac{\rho \overline{U_\infty} c}{\mu} = 1.761 \times 10^4 \qquad \textbf{Eq. C. 32}$$

Where the blade chord, c is 6.740×10^{-3}m, all other values are as before.

According to Blasius, for a flat plate, if $Re_l < 5 \times 10^5$, it represents a laminar boundary layer on a flat plate with zero pressure gradient.

In the region very close to the wall where viscous shear is dominant, the mean velocity profile follows the below linear viscous relation:

$$y^+ = \frac{\rho u_\tau d}{\mu} \qquad \textbf{Eq. C. 33}$$

where d is distance measured from the wall.

All other notations are as before.

By substituting Eq. C 24 into Eq. C. 33;

$$y^+ = \frac{\rho \overline{U_\infty} \left(\sqrt{C_f/2}\right) d}{\mu} \qquad \textbf{Eq. C. 34}$$

According to Blausius' approximate solution for laminar flow over flat plate using sinusoidal velocity profile, the skin-friction coefficient, $C_f = 0.664(Re_l)^{-1/2}$ (Massey 1992). Subsequent to computing Re_l, $C_f = 5.004 \times 10^{-3}$. Rearranging the above equation, if $y^+ \approx 0.3$, d has a value of:

$$d = \frac{y^+ \mu}{\rho \overline{U_\infty} \sqrt{C_f/2}} = \underline{\underline{2.294 \times 10^{-6}\, m}}$$

The same calculation was done to define the distance of first node centre from hub and casing surfaces by using a y^+ value of 30.

C.4 Discretisation Schemes

This section describes the transformations necessary to convert the flow equations described above into a form that may be solved using an orthogonal grid in computational space. A full mathematical description of the transformation is not presented, but the principle is explained. The full mathematics may be found in the CFX Solver Manual.

The basis of the CFX computational code is a conservative finite-difference method, also known as a finite-volume method. All flow variables are defined at the centre of control volumes, which fill the physical domain being considered. Each equation describing the flow is integrated over each control volume to obtain a discrete equation which connects the variable at the centre of the control volume to its values in neighbouring control volumes (CFX Solver Manual 13.3.1).

In principle, if the number of computational cells is large enough, the numerical solution will be indistinguishable from the exact solution of the transport equation. In practice, due to computational constraints, the number of cells may be much smaller than this ideal. The choice of the method used to relate the flow properties at one control volume to its neighbours is crucial in determining the accuracy of the solution.

Various discretisation methods are available in the software ranging from the robust but relatively inaccurate hybrid and first order upwind schemes to the more accurate but less robust higher order schemes. The numerical accuracy of the modelled equations will to a large extent depend upon the method of discretisation chosen for the advection terms. In the course of preliminary investigations a number of different treatments were considered. These are listed below:

- Hybrid differencing (HDS): $1^{st}/2^{nd}$ order accurate. This is a scheme using Central differencing (2^{nd} order accurate) and switch to Upwind differencing (1^{st} order accurate) at Peclet no. (Shaw 1992) greater than 2.
- Higher-order upwind differencing (HUW): 2^{nd} order accurate.
- Quadratic upwind differencing (QUICK): 3^{rd} order accurate for the advection terms, other terms such as diffusion remain only 2^{nd} order.

- CCCT: 3rd order accurate. In particular, the higher order upwinded schemes can suffer from non-physical overshoots in their solutions. For example, turbulent kinetic energy can become negative. CCCT is a modification of the QUICK scheme which is bounded, eliminating these overshoots.

The more accurate the schemes tend to be less robust and slower (CFX Solver Manual). In view of this, CCCT was chosen to be the main discretisation scheme used in the flow modelling for an optimal accurate solution. Whilst, if a solution is difficult to achieve (or the solver tends to fail in a particular case), Hybrid differencing scheme was used instead for the k and ε equations.

C.5 Solution Algorithms

The underlying assumption behind all the previous sections has been that the transport equations for a particular flow property are solved for a particular flow field. For the simulations in this study, the velocity field is not known in advance; it emerges as part of the overall solution as the simulation progresses. This section describes the algorithms used to compute the flow field and generate the transport equations as the simulations progress.

C.5.1 Pressure Correction Method

In most flows of engineering importance, the flow is driven by pressure differences, so that the pressure gradient is the most significant term in the velocity transport equations. For an incompressible flow the pressure and velocity equations are coupled, so that if the correct pressure field has been determined, the velocity field should obey continuity.

In view of the complexity of the governing equations, and because of the linkage between the three-dimensional velocity and pressure fields, an iterative scheme is necessary to determine the flow field for a given set of conditions.

For a given pressure field, it is possible to write discretised momentum equations for each control volume in the flow-field. These equations may be solved to generate the velocity field.

The semi-implicit method for pressure-linked equations (SIMPLE) algorithm of Patankar and Spalding (1972) is the most basic scheme offered within CFX. The method starts from an initial guess of the pressure field, which is then used to determine the velocity field by solving the momentum equations. SIMPLEC is a modification of SIMPLE which differs in its derivation of a simplified momentum equation. A trivial extra amount of work is required for SIMPLEC as compared with SIMPLE, so the cost may be regarded as nearly identical. For a number of model problems, SIMPLEC has proved less sensitive to selection of under-relaxation factors and has required less under-relaxation, so this algorithm is preferred. (CFX Solver Manual 6.2.3)

Once the pressure field has been corrected by the determined amount, the velocity field is recalculated. This flow-field is used to determine the other transport properties. If the solution has converged adequately, the process is stopped. Otherwise, the newly determined properties are used as the first guess for the next iteration.

C.5.2 Under-relaxation factors

Under-relaxation has several interlinked purposes in the solution process. At every iteration, the corrections to the pressure and velocity fields used as input for the transport equations are modified by applying under-relaxation factors (URFs). These factors are used to improve the stability of the solution, particularly if the guessed flow field is far from the true final solution. Pressure is treated differently from the other variables in that the coefficients of the pressure-correction equation are not modified in the way already described. Instead under-relaxation is implemented by adding only a proportion of the pressure-correction onto the pressure:

$$p_{n+1} = p_n + URF_p p' \qquad \textbf{Eq. C. 35}$$

Where: p_n is pressure at the n^{th} iteration,

p' is the pressure correction,

URF_p is the pressure under-relaxation factor.

Under-relaxation is applied to all flow properties. If the values are too high, the solutions will oscillate or diverge, if the values are too small, the solution will converge extremely slowly. The optimum values of URF for each flow variable depend on the flow, and may need to be found heuristically.

For most runs, as recommended by the solver, URF values of 0.65 were used for the variables u, v and w; and 1.0 was used for p. Whilst the optimal URF values of k and ε were both found to be 0.2. If a particular solution was hard to achieve, URF values of u, v and w would be reduced to 0.5; and 0.1 for k and ε.

Appendix D Fortran Routines

To facilitate the simulation, a set of programs must be written to comply with the geometry mesh, and they are included in this section. (1) Command file, which is a file that contains some high-level commands such as the number of steps and iterations to facilitate the simulation; (2) "USRBCS" which allows the calculations and iterative updates of boundary conditions; and the calculations of the various angular momemtum flux terms within the designated boundaries; (3) "USRBF" which allows the calculations of body forces within the domain; (4) "USRGRD" which allows the grid coordinates and calculations to be transformed from Cartesian frame to Cylindrical frame; and, (5) "USRTRN" which allows the calculations of weighted mean flow angles at different axial positions along the domain (for the purpose of evaluating time-varying flow incidence pattern between the rotor inlet-outlet zone).

D.1 Command File

```
/*************************************************************          */
/*                                                                       */
/* TURBULENT (LOW RE K-Epsilon,CCCT)                          */
/* TRANSIENT FLOW - refernce frame - Line graph data                     */
/*************************************************************          */
>>CFX4
  >>SET LIMITS
    MAXIMUM NUMBER OF INTER BLOCK BOUNDARIES 40
  >>OPTIONS
    THREE DIMENSIONS
    BODY FITTED GRID
    CYLINDRICAL COORDINATES
   /*AXIS INCLUDED*/
    TURBULENT FLOW
    ISOTHERMAL FLOW
    INCOMPRESSIBLE FLOW
    TRANSIENT FLOW
    USE DATABASE
    USER SCALAR EQUATIONS 8
  >>USER FORTRAN
     USRBCS
     USRBF
     USRGRD
     USRTRN
   >>VARIABLE NAMES
     USER SCALAR1 'Z SHEAR STRESS'
     USER SCALAR2 'X MASS FLUX'
     USER SCALAR3 'Y MASS FLUX'
     USER SCALAR4 'Z MASS FLUX'
     USER SCALAR5 'ZX NODAL SHEAR STRESS'
     USER SCALAR6 'YZ NODAL SHEAR STRESS'
     USER SCALAR7 'XY NODAL SHEAR STRESS'
     USER SCALAR8 'REAL PRESSURE'
     END
>>MODEL TOPOLOGY
  >>INPUT TOPOLOGY
    READ GEOMETRY FILE
  >>CREATE PATCH
    PATCH TYPE 'INTER BLOCK BOUNDARY'
```

```
    PATCH NAME 'TOP7'
    BLOCK NAME 'BLOCK-NUMBER-7'
    PATCH LOCATION 1 15 1 14 15 15
    HIGH K
  >>CREATE PATCH
    PATCH TYPE 'INTER BLOCK BOUNDARY'
    PATCH NAME 'TOP1'
    BLOCK NAME 'BLOCK-NUMBER-1'
    PATCH LOCATION 1 16 1 14 15 15
    HIGH K
  >>CREATE PATCH
    PATCH TYPE 'INTER BLOCK BOUNDARY'
    PATCH NAME 'TOP2'
    BLOCK NAME 'BLOCK-NUMBER-2'
    PATCH LOCATION 1 16 1 14 15 15
    HIGH K
  >>CREATE PATCH
    PATCH TYPE 'INTER BLOCK BOUNDARY'
    PATCH NAME 'TOP3'
    BLOCK NAME 'BLOCK-NUMBER-3'
    PATCH LOCATION 1 16 1 14 15 15
    HIGH K
  >>CREATE PATCH
    PATCH TYPE 'INTER BLOCK BOUNDARY'
    PATCH NAME 'TOP11'
    BLOCK NAME 'BLOCK-NUMBER-11'
    PATCH LOCATION 1 15 1 14 15 15
    HIGH K
   >>CREATE PATCH
    PATCH TYPE 'INTER BLOCK BOUNDARY'
    PATCH NAME 'BOTTOM7'
    BLOCK NAME 'BLOCK-NUMBER-7'
    PATCH LOCATION 1 15 1 14 1 1
    LOW K
  >>CREATE PATCH
    PATCH TYPE 'INTER BLOCK BOUNDARY'
    PATCH NAME 'BOTTOM8'
    BLOCK NAME 'BLOCK-NUMBER-8'
    PATCH LOCATION 1 16 1 14 1 1
    LOW K
  >>CREATE PATCH
    PATCH TYPE 'INTER BLOCK BOUNDARY'
    PATCH NAME 'BOTTOM9'
    BLOCK NAME 'BLOCK-NUMBER-9'
    PATCH LOCATION 1 16 1 14 1 1
    LOW K
   >>CREATE PATCH
    PATCH TYPE 'INTER BLOCK BOUNDARY'
    PATCH NAME 'BOTTOM10'
    BLOCK NAME 'BLOCK-NUMBER-10'
    PATCH LOCATION 1 16 1 14 1 1
    LOW K
   >>CREATE PATCH
    PATCH TYPE 'INTER BLOCK BOUNDARY'
    PATCH NAME 'BOTTOM11'
    BLOCK NAME 'BLOCK-NUMBER-11'
    PATCH LOCATION 1 15 1 14 1 1
    LOW K
  >>GLUE PATCHES
    FIRST PATCH NAME 'TOP7'
     SECOND PATCH NAME 'BOTTOM7'
    >>GLUE PATCHES
      FIRST PATCH NAME 'TOP1'
      SECOND PATCH NAME 'BOTTOM8'
    >>GLUE PATCHES
      FIRST PATCH NAME 'TOP2'
      SECOND PATCH NAME 'BOTTOM9'
    >>GLUE PATCHES
      FIRST PATCH NAME 'TOP3'
      SECOND PATCH NAME 'BOTTOM10'
    >>GLUE PATCHES
      FIRST PATCH NAME 'TOP11'
      SECOND PATCH NAME 'BOTTOM11'
    END
 >>MODEL DATA
    >>SET INITIAL GUESS
```

```
>>INPUT FROM FILE
  READ DUMP FILE
  UNFORMATTED
  LAST DATA GROUP
  END
>>SELECT VARIABLES FROM FILE
  U VELOCITY
  V VELOCITY
  W VELOCITY
  PRESSURE
  VOLUME FRACTION
  DENSITY
  VISCOSITY
  K
  EPSILON
  BFX FORCE
  BFY FORCE
  BFZ FORCE
  BPX FORCE
  BPY FORCE
  BPZ FORCE
  Z SHEAR STRESS
  X MASS FLUX
  Y MASS FLUX
  Z MASS FLUX
  ZX NODAL SHEAR STRESS
  YZ NODAL SHEAR STRESS
  XY NODAL SHEAR STRESS
  END
>>DIFFERENCING SCHEME
  K 'HYBRID'
  EPSILON 'HYBRID'
  U VELOCITY 'CCCT'
  V VELOCITY 'CCCT'
  W VELOCITY 'CCCT'
  END
>>MATERIALS DATABASE
  >>SOURCE OF DATA
    PCP
  >>FLUID DATA
    FLUID 'WATER'
    MATERIAL TEMPERATURE 2.9400E+02
    MATERIAL PHASE 'LIQUID'
>>PHYSICAL PROPERTIES
  >>TRANSIENT PARAMETERS
    >>FIXED TIME STEPPING
      TIME STEPS 760*1.3888888889E-4
      BACKWARD DIFFERENCE
      INITIAL TIME 0.1000001132
  >>TURBULENCE PARAMETERS
    >>TURBULENCE MODEL
      TURBULENCE MODEL 'LOW REYNOLDS NUMBER K-EPSILON'
>>WALL TREATMENTS
  WALL PROFILE 'LINEAR'
>>TITLE
  PROBLEM TITLE 'TRANSIENT FLOW WITH PERIODIC BOUNDARY LOW'
>>SOLVER DATA
>>PROGRAM CONTROL
  MAXIMUM NUMBER OF ITERATIONS 9
  OUTPUT MONITOR BLOCK 'BLOCK-NUMBER-1'
  OUTPUT MONITOR POINT 3 3 3
  MASS SOURCE TOLERANCE 1.0E-7

  ITERATIONS OF VELOCITY AND PRESSURE EQUATIONS 1
  ITERATIONS OF TURBULENCE EQUATIONS 1
  END
>>UNDER RELAXATION FACTORS
  U VELOCITY 0.5
  V VELOCITY 0.5
  W VELOCITY 0.5
  PRESSURE 1.0
  TE 0.1
  ED 0.1
 /*VISCOSITY 0.6

  BFY 0.6
```

```
    BFZ 0.6
    Z SHEAR STRESS 0.6*/
    END
  >>EQUATION SOLVERS
    ALL PHASES 'AMG'
  >>ALGEBRAIC MULTIGRID PARAMETERS
    CONNECTIVITY TOLERANCE 1.0E-12
    VECTORISED
 /* >>SWEEPS INFORMATION
    >>MINIMUM NUMBER
      K 3
      EPSILON 3
      PRESSURE 30
      U VELOCITY 3
      V VELOCITY 3
      W VELOCITY 3
    >>MAXIMUM NUMBER
      K 10
      EPSILON 10
      PRESSURE 60
      U VELOCITY 15
      V VELOCITY 15
      W VELOCITY 15
>>REDUCTION FACTORS
    K 0.01
    EPSILON 0.01
    PRESSURE 0.01
    U VELOCITY 0.01
    V VELOCITY 0.01
    W VELOCITY 0.01*/
   END
>>MODEL BOUNDARY CONDITIONS
  /*>>SET VARIABLES
    #CALC
     UINL=0.2629547666E+01;
     TEINL=2*0.115*0.115;
     CH=0.012446;
     EPSINL=TEINL**1.5/(0.3*CH);
    #ENDCALC
    PATCH NAME 'INLET'
    U VELOCITY #UINL
    V VELOCITY 0.00
    W VELOCITY 0.00
    K #TEINL
    EPSILON #EPSINL
    END
  >>SET VARIABLES
    PATCH NAME 'OUTLET'
    PRESSURE 2.0E5*/
  >>WALL BOUNDARY CONDITIONS
    PATCH NAME 'HUB1'
    TAUX 0.0
  >>WALL BOUNDARY CONDITIONS
    PATCH NAME 'HUB2'
    TAUX 0.0
  >>WALL BOUNDARY CONDITIONS
    PATCH NAME 'HUB3'
    TAUX 0.0
  >>WALL BOUNDARY CONDITIONS
    PATCH NAME 'HUB4'
    TAUX 0.0
  >>WALL BOUNDARY CONDITIONS
    PATCH NAME 'HUB5'
    TAUX 0.0
  >>WALL BOUNDARY CONDITIONS
    PATCH NAME 'HUB6'
    TAUX 0.0
  >>WALL BOUNDARY CONDITIONS
    PATCH NAME 'HUB7'
    TAUX 0.0
  >>WALL BOUNDARY CONDITIONS
    PATCH NAME 'HUB8'
    TAUX 0.0
  >>WALL BOUNDARY CONDITIONS
    PATCH NAME 'HUB9'
    TAUX 0.0
```

```
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'HUB10'
  TAUX 0.0
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'HUB11'
  TAUX 0.0
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'CASE1'
  TAUX 0.0
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'CASE2'
  TAUX 0.0
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'CASE3'
  TAUX 0.0
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'CASE4'
  TAUX 0.0
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'CASE5'
  TAUX 0.0
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'CASE6'
  TAUX 0.0
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'CASE7'
  TAUX 0.0
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'CASE8'
  TAUX 0.0
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'CASE9'
  TAUX 0.0
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'CASE10'
  TAUX 0.0
>>WALL BOUNDARY CONDITIONS
  PATCH NAME 'CASE11'
  TAUX 0.0
>>OUTPUT OPTIONS
  >>LINE GRAPH DATA
    FILE NAME 'RESIDUALS'
    RESIDUAL
    EACH ITERATION
    ALL VARIABLES
  >>PRINT OPTIONS
    >>WHAT
      NO WALL PRINTING
    >>WHEN
      FINAL SOLUTION
      END
    >>WHERE
      J PLANES 8
>>STOP
```

D.2 USRBCS

```
      SUBROUTINE USRBCS(VARBCS,VARAMB,A,B,C,ACND,BCND,CCND
     +                  ,IWGVEL,NDVWAL
     +                  ,FLOUT,NLABEL,NSTART,NEND,NCST,NCEN
     +                  ,U,V,W,P,VFRAC,DEN,VIS,TE,ED,RS,T,H,RF,SCAL
     +                  ,XP,YP,ZP,VOL,AREA,VPOR,ARPOR,WFACT,IPT
     +                  ,IBLK,IPVERT,IPNODN,IPFACN,IPNODF,IPNODB,IPFACB
     +                  ,WORK,IWORK,CWORK)
C
C*****************************************************************************
C
C  USER ROUTINE TO SET REALS AT BOUNDARIES.
C
C   >>> IMPORTANT                                                        <<<
C   >>>                                                                 <<<
C   >>> USERS MAY ONLY ADD OR ALTER PARTS OF THE SUBROUTINE WITHIN  <<<
C   >>> THE DESIGNATED USER AREAS                                       <<<
C
C*****************************************************************************
C
C  THIS SUBROUTINE IS CALLED BY THE FOLLOWING SUBROUTINE
C    CUSR  SRLIST
C
C*****************************************************************************
C   CREATED
C      30/11/88 ADB
C   MODIFIED
C      08/09/90 ADB  RESTRUCTURED FOR USER-FRIENDLINESS.
C      10/08/91 IRH  FURTHER RESTRUCTURING ADD ACND BCND CCND
C      22/09/91 IRH  CHANGE ICALL TO IUCALL + ADD /SPARM/
C      10/03/92 PHA  UPDATE CALLED BY COMMENT, ADD RF ARGUMENT,
C                    CHANGE LAST DIMENSION OF RS TO 6 AND IVERS TO 2
C      03/06/92 PHA  ADD PRECISION FLAG AND CHANGE IVERS TO 3
C      30/06/92 NSW  INCLUDE FLAG FOR CALLING BY ITERATION
C                    INSERT EXTRA COMMENTS
C      03/08/92 NSW  MODIFY DIMENSION STATEMENTS FOR VAX
C      21/12/92 CSH  INCREASE IVERS TO 4
C      02/08/93 NSW  INCORRECT AND MISLEADING COMMENT REMOVED
C      05/11/93 NSW  INDICATE USE OF FLOUT IN MULTIPHASE FLOWS

C      23/11/93 CSH  EXPLICITLY DIMENSION IPVERT ETC.
C      01/02/94 NSW  SET VARIABLE POINTERS IN WALL EXAMPLE.
C                    CHANGE FLOW3D TO CFDS-FLOW3D.
C                    MODIFY MULTIPHASE MASS FLOW BOUNDARY TREATMENT.
C      03/03/94 FHW  CORRECTION OF SPELLING MISTAKE
C      02/07/94 BAS  SLIDING GRIDS - ADD NEW ARGUMENT IWGVEL
C                    TO ALLOW VARIANTS OF TRANSIENT-GRID WALL BC
C                    CHANGE VERSION NUMBER TO 5
C      09/08/94 NSW  CORRECT SPELLING
C                    MOVE 'IF(IUSED.EQ.0) RETURN' OUT OF USER AREA
C      19/12/94 NSW  CHANGE FOR CFX-F3D
C      02/02/95 NSW  CHANGE COMMON /IMFBMP/
C      02/06/97 NSW  MAKE EXAMPLE MORE LOGICAL
C      02/07/97 NSW  UPDATE FOR CFX-4
C
C*****************************************************************************
C
C   SUBROUTINE ARGUMENTS
C
C     VARBCS - REAL BOUNDARY CONDITIONS
C     VARAMB - AMBIENT VALUE OF VARIABLES
C     A      - COEFFICIENT IN WALL BOUNDARY CONDITION
C     B      - COEFFICIENT IN WALL BOUNDARY CONDITION
C     C      - COEFFICIENT IN WALL BOUNDARY CONDITION
C     ACND   - COEFFICIENT IN CONDUCTING WALL BOUNDARY CONDITION
C     BCND   - COEFFICIENT IN CONDUCTING WALL BOUNDARY CONDITION
C     CCND   - COEFFICIENT IN CONDUCTING WALL BOUNDARY CONDITION
C     IWGVEL - USAGE OF INPUT VELOCITIES (0 = AS IS,1 = ADD GRID MOTION)
C     NDVWAL - FIRST DIMENSION OF ARRAY IWGVEL
C     FLOUT  - MASS FLOW/FRACTIONAL MASS FLOW
C     NLABEL - NUMBER OF DISTINCT OUTLETS
C     NSTART - ARRAY POINTER
C     NEND   - ARRAY POINTER
```

```
C       NCST    - ARRAY POINTER
C       NCEN    - ARRAY POINTER
C       U       - U COMPONENT OF VELOCITY
C       V       - V COMPONENT OF VELOCITY
C       W       - W COMPONENT OF VELOCITY
C       P       - PRESSURE
C       VFRAC   - VOLUME FRACTION
C       DEN     - DENSITY OF FLUID
C       VIS     - VISCOSITY OF FLUID
C       TE      - TURBULENT KINETIC ENERGY
C       ED      - EPSILON
C       RS      - REYNOLD STRESSES
C       T       - TEMPERATURE
C       H       - ENTHALPY
C       RF      - REYNOLD FLUXES
C       SCAL    - SCALARS (THE FIRST 'NCONC' OF THESE ARE MASS FRACTIONS)
C       XP      - X COORDINATES OF CELL CENTRES
C       YP      - Y COORDINATES OF CELL CENTRES
C       ZP      - Z COORDINATES OF CELL CENTRES
C       VOL     - VOLUME OF CELLS
C       AREA    - AREA OF CELLS
C       VPOR    - POROUS VOLUME
C       ARPOR   - POROUS AREA
C       WFACT   - WEIGHT FACTORS
C
C       IPT     - 1D POINTER ARRAY
C       IBLK    - BLOCK SIZE INFORMATION
C       IPVERT  - POINTER FROM CELL CENTERS TO 8 NEIGHBOURING VERTICES
C       IPNODN  - POINTER FROM CELL CENTERS TO 6 NEIGHBOURING CELLS
C       IPFACN  - POINTER FROM CELL CENTERS TO 6 NEIGHBOURING FACES
C       IPNODF  - POINTER FROM CELL FACES TO 2 NEIGHBOURING CELL CENTERS
C       IPNODB  - POINTER FROM BOUNDARY CENTERS TO CELL CENTERS
C       IPFACB  - POINTER TO NODES FROM BOUNDARY FACES
C
C       WORK    - REAL WORKSPACE ARRAY
C       IWORK   - INTEGER WORKSPACE ARRAY
C       CWORK   - CHARACTER WORKSPACE ARRAY
C
C    SUBROUTINE ARGUMENTS PRECEDED WITH A '*' ARE ARGUMENTS THAT MUST
C    BE SET  BY THE USER IN THIS ROUTINE.
C
C    NOTE THAT OTHER DATA MAY BE OBTAINED FROM CFX-4 USING THE
C    ROUTINE GETADD, FOR FURTHER DETAILS SEE THE VERSION 4
C    USER MANUAL.
C
C*************************************************************************
      LOGICAL LDEN,LVIS,LTURB,LTEMP,LBUOY,LSCAL,LCOMP
     +       ,LRECT,LCYN,LAXIS,LPOROS,LTRANS
C
      CHARACTER*(*) CWORK
C
C+++++++++++++++++ USER AREA 1+++++++++++++++++++++++++++++++++++++++++
C---- AREA FOR USERS EXPLICITLY DECLARED VARIABLES
C
      REAL TSUM,INERTIA,ACCE,AREAM,WOLD,WTEMP,WNEW,UOLD,UNEW,WABS,
     +     WVSUM,VSUM,DELTAR,TNET,
     +     AMP,FREQ,PERIOD,OMEGA,REMAIN,PHASE,RADIAN,PULSE,
     +     MOINA,MOINB,MOINC,MOIND,MOOUTA,MOOUTB,MOOUTC,MOOUTD,
     +     FIAOLD,FIANEW,FIBOLD,FIBNEW,FIAOLDP,FIANEWP,FIBOLDP,FIBNEWP,
     +     TROTOR,TFIA,TFIB,TFIAP,TFIBP,TFRIC,MASSIA,MASSIC,MASSO,
     +     THETAXO,RTHETAO,XRO,XTHETAO,
     +     THETAXJ,RTHETAJ,XRJ,XTHETAJ,
     +     THETAXD,RTHETAD,XRD,XTHETAD,
     +     THETAXP,RTHETAP,XRP,XTHETAP,UA
      INTEGER ITXT,ISEQF,BLADEN,DOMAINN,IUSRITER,IUSRSTEP
C
C+++++++++++++++++ END OF USER AREA 1+++++++++++++++++++++++++++++++++++
C
      COMMON
     + /ALL/     NBLOCK,NCELL,NBDRY,NNODE,NFACE,NVERT,NDIM
     + /ALLWRK/  NRWS,NIWS,NCWS,IWRFRE,IWIFRE,IWCFRE
     + /ADDIMS/  NPHASE,NSCAL,NVAR,NPROP
     +          ,NDVAR,NDPROP,NDXNN,NDGEOM,NDCOEF,NILIST,NRLIST,NTOPOL
     + /BCSOUT/  IFLOUT
     + /CHKUSR/  IVERS,IUCALL,IUSED
     + /DEVICE/  NREAD,NWRITE,NRDISK,NWDISK
```

```
     + /IDUM/    ILEN,JLEN
     + /IMFBMP/  IMFBMP,JMFBMP
     + /LOGIC/   LDEN,LVIS,LTURB,LTEMP,LBUOY,LSCAL,LCOMP
     +          ,LRECT,LCYN,LAXIS,LPOROS,LTRANS
     + /MLTGRD/  MLEVEL,NLEVEL,ILEVEL
     + /SGLDBL/  IFLGPR,ICHKPR
     + /SPARM/   SMALL,SORMAX,NITER,INDPRI,MAXIT,NODREF,NODMON
     + /TRANSI/  NSTEP,KSTEP,MF,INCORE
     + /TIMUSR/  DTUSR
     + /TRANSR/  TIME,DT,DTINVF,TPARM
     + /UBCSFL/  IUBCSF
C
C+++++++++++++++++ USER AREA 2++++++++++++++++++++++++++++++++++++++++++
C---- AREA FOR USERS TO DECLARE THEIR OWN COMMON BLOCKS
C     THESE SHOULD START WITH THE CHARACTERS 'UC' TO ENSURE
C     NO CONFLICT WITH NON-USER COMMON BLOCKS
      COMMON
     +  /UC1/ TSUM,INERTIA,ACCE,AREAM,WOLD,WTEMP,WNEW,UOLD,UNEW,WABS,
     +     WVSUM,VSUM,DELTAR,TNET,
     +     AMP,FREQ,PERIOD,OMEGA,REMAIN,PHASE,RADIAN,PULSE,
     +     MOINA,MOINB,MOINC,MOIND,MOOUTA,MOOUTB,MOOUTC,MOOUTD,
     +     FIAOLD,FIANEW,FIBOLD,FIBNEW,FIAOLDP,FIANEWP,FIBOLDP,FIBNEWP,
     +     TROTOR,TFIA,TFIB,TFIAP,TFIBP,TFRIC,MASSIA,MASSIC,MASSO,
     +     THETAXO,RTHETAO,XRO,XTHETAO,
     +     THETAXJ,RTHETAJ,XRJ,XTHETAJ,
     +     THETAXD,RTHETAD,XRD,XTHETAD,
     +     THETAXP,RTHETAP,XRP,XTHETAP,UA
C
C+++++++++++++++++ END OF USER AREA 2++++++++++++++++++++++++++++++++++++
C
      DIMENSION
     + VARBCS(NVAR,NPHASE,NCELL+1:NNODE),VARAMB(NVAR,NPHASE)
     +,A(4+NSCAL,NPHASE,NSTART:*)
     +,B(4+NSCAL,NPHASE,NSTART:*),C(4+NSCAL,NPHASE,NSTART:*)
     +,FLOUT(*),ACND(NCST:*),BCND(NCST:*),CCND(NCST:*)
     +,IWGVEL(NDVWAL,NPHASE)
C
      DIMENSION
     + U(NNODE,NPHASE),V(NNODE,NPHASE),W(NNODE,NPHASE),P(NNODE,NPHASE)
     +,VFRAC(NNODE,NPHASE),DEN(NNODE,NPHASE),VIS(NNODE,NPHASE)
     +,TE(NNODE,NPHASE),ED(NNODE,NPHASE),RS(NNODE,NPHASE,6)
     +,T(NNODE,NPHASE),H(NNODE,NPHASE),RF(NNODE,NPHASE,4)
     +,SCAL(NNODE,NPHASE,NSCAL)
C
      DIMENSION
     + XP(NNODE),YP(NNODE),ZP(NNODE)
     +,VOL(NCELL),AREA(NFACE,3),VPOR(NCELL),ARPOR(NFACE,3),WFACT(NFACE)
     +,IPT(*),IBLK(5,NBLOCK)
     +,IPVERT(NCELL,8),IPNODN(NCELL,6),IPFACN(NCELL,6),IPNODF(NFACE,4)
     +,IPNODB(NBDRY,4),IPFACB(NBDRY)
     +,IWORK(*),WORK(*),CWORK(*)
C
C+++++++++++++++++ USER AREA 3++++++++++++++++++++++++++++++++++++++++++
C---- AREA FOR USERS TO DIMENSION THEIR ARRAYS
C
      CHARACTER *15 USRBLADE,USRDOM
      DIMENSION USRBLADE(0:50),USRDOM(0:11)
      REAL   USRPRESS(10,20,30),USRMEAN(20),
     +       USRRAD(20,30)
C---- AREA FOR USERS TO DEFINE DATA STATEMENTS
C
C+++++++++++++++++ END OF USER AREA 3++++++++++++++++++++++++++++++++++++
C
C---- STATEMENT FUNCTION FOR ADDRESSING
      IP(I,J,K)=IPT((K-1)*ILEN*JLEN+(J-1)*ILEN+I)
C
C----VERSION NUMBER OF USER ROUTINE AND PRECISION FLAG
C
      IVERS=5
      ICHKPR = 1
C
C+++++++++++++++++ USER AREA 4++++++++++++++++++++++++++++++++++++++++++
C---- TO USE THIS USER ROUTINE FIRST SET IUSED=1
       IUSED=1
C     AND SET IUBCSF FLAG:
C     BOUNDARY CONDITIONS NOT CHANGING
```

```
C       IUBCSF=0
C      BOUNDARY CONDITIONS CHANGING WITH ITERATION
C       IUBCSF=1
C      BOUNDARY CONDITIONS CHANGING WITH TIME
C       IUBCSF=2
C      BOUNDARY CONDITIONS CHANGING WITH TIME AND ITERATION
        IUBCSF=3
C++++++++++++++++++ END OF USER AREA 4++++++++++++++++++++++++++++++++++
C
        IF (IUSED.EQ.0) RETURN
C
C---- FRONTEND CHECKING OF USER ROUTINE
        IF (IUCALL.EQ.0) RETURN
C
C++++++++++++++++++ USER AREA 5++++++++++++++++++++++++++++++++++++++++
         IPHASE=1
C
C        IF (KSTEP.EQ.0) THEN
C         ISEQF=0
C         CALL FILCON('USRBCS','tsum.txt','OPEN','FORMATTED',
C     +              'NEW',ITXT,ISEQF,IOST,IERR)
C
C         IF (IERR.NE.0) THEN
C         CALL FILERR('USRBCS','tsum.txt','OPEN','NEW',
C     +                ITXT,ISEQF,IOST,IERR)
C         END IF
C        ENDIF
C
C----INITIAL CONDITIONS FOR RESTART
C
       IUSRITER=9
       IUSRSTEP=760
C
       IF (NITER.LE.1) THEN
C
        IF (KSTEP.EQ.0) THEN
          UNEW=0.2629547596E+01
         WNEW=-0.3998958130E+03
         WOLD=-0.3998956604E+03
          FIAOLD=-1.754262513E-07
          FIANEW=-1.754303014E-07
          FIBOLD=1.516304837E-05
          FIBNEW=1.516306384E-05
          FIAOLDP=-1.020277622E-07
          FIANEWP=-1.020272293E-07
          FIBOLDP=3.917623417E-06
          FIBNEWP=3.917619324E-06
           DT=0.0005
          UOLD=UNEW
           AMP=0.4198
           FREQ=20
         PERIOD=1/FREQ
          OMEGA=2*3.14159265359/PERIOD
        ELSE
C
C---- SET WOLD EQUALS TO THE ANGULAR VELOCITY AT THE TIME STEP
C

        WOLD=WNEW
        FIAOLD=FIANEW
         FIBOLD=FIBNEW
         FIAOLDP=FIANEWP
         FIBOLDP=FIBNEWP
         ENDIF
        ENDIF
C
C---- TO FIND THE ANGULAR ACCELERATION OF THE BLADE AT EACH TIME STEP
C
        AREAM=0.0
        TSUM=0.0
        TNET=0.0
        WABS=0.0
        WVSUM=0.0
        VSUM=0.0
        MOINA=0.0
        MOINB=0.0
```

```
      MOINC=0.0
      MOIND=0.0
      MOOUTA=0.0
      MOOUTB=0.0
      MOOUTC=0.0
      MOOUTD=0.0
       MASSIA=0.0
       MASSIC=0.0
       MASSO=0.0
       THETAXO=0.0
       RTHETAO=0.0
           XRO=0.0
       XTHETAO=0.0
       THETAXJ=0.0
       RTHETAJ=0.0
           XRJ=0.0
       XTHETAJ=0.0
       THETAXD=0.0
       RTHETAD=0.0
           XRD=0.0
       XTHETAD=0.0
       THETAXP=0.0
       RTHETAP=0.0
           XRP=0.0
       XTHETAP=0.0
      IF (NITER.EQ.IUSRITER) THEN
        FIANEW=0.0
        FIBNEW=0.0
        FIANEWP=0.0
        FIBNEWP=0.0
      ENDIF
      INERTIA=3.24885667E-09
C
C
C---- SET BLADEN TO BE BLADE1 TO BLADE6
      USRBLADE(1)='BLADE1'
      USRBLADE(2)='BLADE2'
      USRBLADE(3)='BLADE3'
      USRBLADE(4)='BLADE4'
      USRBLADE(5)='BLADE5'
      USRBLADE(6)='BLADE6'
C
      DO 134 BLADEN=1,6
      CALL IPREC(USRBLADE(BLADEN),'PATCH','CENTRES',IPT,
     +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C---- GET SCALAR NUMBER CORRESPONDING TO THETA(Z) SHEAR STRESS
C
       CALL GETSCA ('Z SHEAR STRESS',ICS1,CWORK)
C
C---- LOOP OVER ALL WALL CELL CENTRES LOCATION IN WALLS
C
C234567891123456789212345678931234567894123456789512345678961233456789712
C     LOOP OVER PATCH
C
       DO 133 K=1,KLEN
          DO 132 J=1,JLEN
             DO 131 I=1,ILEN
C
C     USE STATEMENT FUNCTION IP TO GET ADDRESSES
            INODE=IP(I,J,K)
             IBDRY=INODE-NCELL
             IFACE=IPFACB(IBDRY)
             AREAM=SQRT(AREA(IFACE,1)**2+
     +                  AREA(IFACE,2)**2+
     +                  AREA(IFACE,3)**2)
C
            TSUM=TSUM-P(INODE,1)*YP(INODE)*AREA(IFACE,3)-
     +           YP(INODE)*SCAL(INODE,1,ICS1)*AREAM
C
       IF ((NITER.EQ.IUSRITER).AND.(KSTEP.EQ.IUSRSTEP)) THEN
       WRITE(ITXT,900)I,J,K,P(INODE,1),SCAL(INODE,1,ICS1),XP(INODE),
     +  YP(INODE),ZP(INODE),AREA(IFACE,1),AREA(IFACE,2),AREA(IFACE,3),
     +  AREAM,TSUM
 900    FORMAT(I5,I5,I5,10(2X,E17.10))
       ENDIF
```

```
C
 131    CONTINUE
 132    CONTINUE
 133    CONTINUE
 134    CONTINUE
C
C
C
        IF (KSTEP.EQ.0) THEN
         ACCE=-3.349977136E-01
        ELSE
         TFRIC=0.0
          TNET=TSUM+TFRIC
         ACCE=TNET/INERTIA
        ENDIF
C
C
C---- TO UPDATE THE INLET FLOW VELOCITY USING 1ST ORDER
C---- BACKWARD DIFFERENCING
C
C---- OPEN THE FILE CONTAINING DATA ABOUT ANGULAR VELOCITY(WNEW)
C234567891123456789212345678931234567894123456789512345678961233456789712
       IF (KSTEP.EQ.0) THEN
        ISEQF=0
         CALL FILCON('USRBCS','angular.txt','OPEN','FORMATTED',
     +             'NEW',ITXT,ISEQF,IOST,IERR)
C
         IF (IERR.NE.0) THEN
         CALL FILERR('USRBCS','angular.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
        END IF
       ENDIF
C
C
C
        IF (KSTEP.EQ.40) THEN
        REMAIN=TIME/PERIOD-INT(TIME/PERIOD)
        PHASE=PERIOD*REMAIN
        ENDIF
C
        IF ((NITER.EQ.1).AND.(KSTEP.GE.41)) THEN
         RADIAN=OMEGA*(TIME-PHASE)
         PULSE=AMP*SIN(RADIAN)
           UNEW=UOLD*(1+PULSE)
         ENDIF
C
C---- SET WNEW TO THE VELOCITY AT THE NEXT TIME STEP
C
       WNEW = WOLD+ACCE*DT
C
       IF (KSTEP.GE.1) THEN
       CALL GETSCA ('X MASS FLUX',ICS2,CWORK)
       CALL GETSCA ('Y MASS FLUX',ICS3,CWORK)
       CALL GETSCA ('Z MASS FLUX',ICS4,CWORK)
       CALL GETSCA ('ZX NODAL SHEAR STRESS',ICS5,CWORK)
       CALL GETSCA ('YZ NODAL SHEAR STRESS',ICS6,CWORK)
       CALL GETSCA ('XY NODAL SHEAR STRESS',ICS7,CWORK)
       ENDIF
C
C234567891123456789212345678931234567894123456789512345678961233456789712
       CALL IPREC('INLET','PATCH','CENTRES',IPT,
      +           ILEN,JLEN,KLEN,CWORK,IWORK)
C      INTERROGATE GETVAR FOR VARIABLE NUMBERS
C
        CALL GETVAR('USRBCS','W      ',IW)
        CALL GETVAR('USRBCS','U      ',IU)
C
C      LOOP OVER PATCH
        DO 103 K=1,KLEN
           DO 102 J=1,JLEN
              DO 101 I=1,ILEN
C
C      USE STATEMENT FUNCTION IP TO GET ADDRESSES
             INODE=IP(I,J,K)
C
C      SET VARBCS
```

```
            VARBCS(IW,IPHASE,INODE) = -YP(INODE)*WNEW
          IF (KSTEP.LE.40) THEN
               VARBCS(IU,IPHASE,INODE) = 0.2629547596E+01
          ELSE
               VARBCS(IU,IPHASE,INODE) = UNEW
          ENDIF
C
C
        IF (NITER.EQ.IUSRITER) THEN
              IBDRY=INODE-NCELL
              IFACE=IPFACB(IBDRY)
             WABS = W(INODE,1)+YP(INODE)*WNEW
C234567891123456789212345678931234567894123456789512345678961233456789712
        MOINA =MOINA+DEN(INODE,1)*YP(INODE)*U(INODE,1)*WABS*AREA(IFACE,1)
        MOINB =MOINB+DEN(INODE,1)*YP(INODE)*U(INODE,1)*W(INODE,1)
     +           *AREA(IFACE,1)
C
        MASSIA=MASSIA+SCAL(INODE,1,ICS2)*AREA(IFACE,1)+SCAL(INODE,1,ICS3)
     +        *AREA(IFACE,2)+SCAL(INODE,1,ICS4)*AREA(IFACE,3)
C
           IF (KSTEP.EQ.IUSRSTEP) THEN
        WRITE(ITXT,901)I,J,K,P(INODE,1),VOL(INODE),WNEW,WABS,U(INODE,1),
     +  V(INODE,1),W(INODE,1),YP(INODE),
     +  AREA(IFACE,1),AREA(IFACE,2),AREA(IFACE,3)
 901     FORMAT(I5,I5,I5,11(2X,E17.10))
           ENDIF
C
        ENDIF
 101        CONTINUE
 102      CONTINUE
 103    CONTINUE
C
C
C---- TO LOCATE JUST UPSTREAM FINDING ANG. MOMENTUM
C
        IF (NITER.EQ.IUSRITER) THEN
        CALL IPREC('BLOCK-NUMBER-7','BLOCK','CENTRES',IPT,
     +            ILEN,JLEN,KLEN,CWORK,IWORK)
C      INTERROGATE GETVAR FOR VARIABLE NUMBERS
C
C      LOOP OVER PATCH
          I=14
            DO 161 J=1,JLEN
             DO 162 K=1,KLEN
C
C      USE STATEMENT FUNCTION IP TO GET ADDRESSES
               INODE=IP(I,J,K)
            WABS = W(INODE,1)+YP(INODE)*WNEW
            UA=U(INODE,1)*AREA(INODE,1)+V(INODE,1)*AREA(INODE,2)+
     +           W(INODE,1)*AREA(INODE,3)
C
C234567891123456789212345678931234567894123456789512345678961233456789712
         MOINC =MOINC+DEN(INODE,1)*YP(INODE)*WABS*UA
         MOIND =MOIND+DEN(INODE,1)*YP(INODE)*W(INODE,1)*UA
C
         MASSIC=MASSIC+SCAL(INODE,1,ICS2)*AREA(INODE,1)+SCAL(INODE,1,ICS3)
     +         *AREA(INODE,2)+SCAL(INODE,1,ICS4)*AREA(INODE,3)
C
           IF (KSTEP.EQ.IUSRSTEP) THEN
C234567891123456789212345678931234567894123456789512345678961233456789712
         WRITE(ITXT,902)I,J,K,P(INODE,1),VOL(INODE),WNEW,WABS,
     +   U(INODE,1),V(INODE,1),W(INODE,1),YP(INODE),
     +   AREA(INODE,1),AREA(INODE,2),AREA(INODE,3)
 902     FORMAT(I5,I5,I5,11(2X,E17.10))
         ENDIF
C
C
 162       CONTINUE
 161       CONTINUE
         ENDIF
C
C
C---- SET RADIAL EQUILIBRIUM FOR PRESSURE AT OUTLET
C
C---- TO FIND WABSMEAN=USRMEAN(J) FOR EACH J
        CALL IPREC('BLOCK-NUMBER-11','BLOCK','CENTRES',IPT,
```

```
     +            ILEN,JLEN,KLEN,CWORK,IWORK)
C     INTERROGATE GETVAR FOR VARIABLE NUMBERS
C
C     LOOP OVER PATCH
        I=ILEN
          DO 141 J=1,JLEN
           WVSUM=0.0
           VSUM=0.0
           DO 140 K=1,KLEN
C
C     USE STATEMENT FUNCTION IP TO GET ADDRESSES
             INODE=IP(I,J,K)
          USRRAD(J,K)=YP(INODE)
         WABS = W(INODE,1)+YP(INODE)*WNEW
         WVSUM = WVSUM + WABS*VOL(INODE)
          VSUM = VSUM +VOL(INODE)
C
        IF (K.EQ.KLEN) THEN
          USRMEAN(J) = WVSUM/VSUM
        ENDIF
C
        IF (NITER.EQ.IUSRITER) THEN
C23456789112345678921234567893123456789412345678951234567896123345678971 2
        MOOUTA=MOOUTA+DEN(INODE,1)*YP(INODE)*U(INODE,1)*WABS
     +           *AREA(INODE,1)
        MOOUTB=MOOUTB+DEN(INODE,1)*YP(INODE)*U(INODE,1)*W(INODE,1)
     +           *AREA(INODE,1)
C
        MASSO=MASSO+SCAL(INODE,1,ICS2)*AREA(INODE,1)+SCAL(INODE,1,ICS3)*
     +       AREA(INODE,2)+SCAL(INODE,1,ICS4)*AREA(INODE,3)
C
C
        THETAXO=THETAXO+YP(INODE)*SCAL(INODE,1,ICS5)*AREA(INODE,3)
        RTHETAO=RTHETAO+YP(INODE)*SCAL(INODE,1,ICS6)*AREA(INODE,2)
            XRO=XRO+YP(INODE)*SCAL(INODE,1,ICS7)*AREA(INODE,1)
        XTHETAO=XTHETAO+YP(INODE)*SCAL(INODE,1,ICS5)*AREA(INODE,1)
C
         IF (KSTEP.EQ.IUSRSTEP) THEN
C23456789112345678921234567893123456789412345678951234567896123345678971 2
         WRITE(ITXT,903)I,J,K,P(INODE,1),VOL(INODE),WNEW,WABS,WVSUM,VSUM,
     +   U(INODE,1),V(INODE,1),W(INODE,1),YP(INODE),USRMEAN(J),
     +   USRRAD(J,K),AREA(INODE,1),AREA(INODE,2),AREA(INODE,3)
 903     FORMAT(I5,I5,I5,15(2X,E17.10))
        ENDIF
C
        ENDIF
C
C
 140     CONTINUE
 141     CONTINUE
C
      CALL IPREC('OUTLET','PATCH','CENTRES',IPT,
     +           ILEN,JLEN,KLEN,CWORK,IWORK)
C     INTERROGATE GETVAR FOR VARIABLE NUMBERS
      CALL GETVAR('USRBCS','P     ',IPRES)
C
C     LOOP OVER PATCH
        DO 142 I=1,ILEN
          DO 143 J=1,JLEN
            WVSUM=0.0
            VSUM=0.0
            DO 144 K=1,KLEN
C
C     USE STATEMENT FUNCTION IP TO GET ADDRESSES
             INODE=IP(I,J,K)
C
          IF (J.EQ.1) THEN
           USRPRESS(I,J,K) = 0.0
          ENDIF
          IF (J.GT.1) THEN
           DELTAR=YP(INODE)-USRRAD(J-1,K)
           USRPRESS(I,J,K) = USRPRESS(I,J-1,K)+DEN(INODE,1)*USRMEAN(J)
     +      **2.0*DELTAR/YP(INODE)
          ENDIF
C
C     SET VARBCS
```

```
            VARBCS(IPRES,IPHASE,INODE) = USRPRESS(I,J,K)
C
       IF ((NITER.EQ.IUSRITER).AND.(KSTEP.EQ.IUSRSTEP)) THEN
             IBDRY=INODE-NCELL
             IFACE=IPFACB(IBDRY)
         WABS = W(INODE,1)+YP(INODE)*WNEW
         WVSUM = WVSUM + WABS*VOL(INODE)
          VSUM = VSUM +VOL(INODE)
       WRITE(ITXT,904)I,J,K,P(INODE,1),VOL(INODE),WNEW,WABS,WVSUM,VSUM,
     +  U(INODE,1),V(INODE,1),W(INODE,1),YP(INODE),USRMEAN(J),
     +  USRRAD(J-1,K),AREA(IFACE,1),AREA(IFACE,2),AREA(IFACE,3),
     +  USRPRESS(I,J,K)
 904    FORMAT(I5,I5,I5,16(2X,E17.10))
       ENDIF
C
 144     CONTINUE
 143     CONTINUE
 142     CONTINUE
C
C
C
C---- TO FIND ANGULAR MOMENTUM AT JUST DOWNSTREAM
       IF (NITER.EQ.IUSRITER) THEN
       CALL IPREC('BLOCK-NUMBER-11','BLOCK','CENTRES',IPT,
     +            ILEN,JLEN,KLEN,CWORK,IWORK)
C      INTERROGATE GETVAR FOR VARIABLE NUMBERS
C
C      LOOP OVER PATCH
         I=2
           DO 121 J=1,JLEN
            DO 120 K=1,KLEN
C
C      USE STATEMENT FUNCTION IP TO GET ADDRESSES
             INODE=IP(I,J,K)
             WABS = W(INODE,1)+YP(INODE)*WNEW
               UA=U(INODE,1)*AREA(INODE,1)+V(INODE,1)*AREA(INODE,2)+
     +          W(INODE,1)*AREA(INODE,3)
C
C234567891123456789212345678931234567894123456789512345678961233456789712
       MOOUTC =MOOUTC+DEN(INODE,1)*YP(INODE)*WABS*UA
       MOOUTD =MOOUTD+DEN(INODE,1)*YP(INODE)*W(INODE,1)*UA
C
C
       THETAXJ=THETAXJ+YP(INODE)*SCAL(INODE,1,ICS5)*AREA(INODE,3)
       RTHETAJ=RTHETAJ+YP(INODE)*SCAL(INODE,1,ICS6)*AREA(INODE,2)
           XRJ=XRJ+YP(INODE)*SCAL(INODE,1,ICS7)*AREA(INODE,1)
       XTHETAJ=XTHETAJ+YP(INODE)*SCAL(INODE,1,ICS5)*AREA(INODE,1)
C
        IF (KSTEP.EQ.IUSRSTEP) THEN
C234567891123456789212345678931234567894123456789512345678961233456789712
       WRITE(ITXT,905)I,J,K,P(INODE,1),VOL(INODE),WNEW,WABS,
     +  U(INODE,1),V(INODE,1),W(INODE,1),YP(INODE),
     +  AREA(INODE,1),AREA(INODE,2),AREA(INODE,3),
     +  AREA(INODE,4),AREA(INODE,5),AREA(INODE,6),UA
 905    FORMAT(I5,I5,I5,15(2X,E17.10))
        ENDIF
C
 120     CONTINUE
 121     CONTINUE
       ENDIF
C
       IF (NITER.EQ.IUSRITER) THEN
C-------TO FIND OUT THE FLUID MOMENTUM FLUX ACROSS THE DOMAIN
        CALL IPALL('*','*','BLOCK','CENTRES',IPT,NPT,CWORK,IWORK)
C
        DO 150 I=1,NPT
               INODE=IPT(I)
C
        WABS = W(INODE,1)+YP(INODE)*WNEW
        FIANEW = FIANEW+DEN(INODE,1)*YP(INODE)*WABS*VOL(INODE)
        FIBNEW = FIBNEW+DEN(INODE,1)*YP(INODE)*W(INODE,1)*VOL(INODE)
C
       THETAXD=THETAXD+YP(INODE)*SCAL(INODE,1,ICS5)*AREA(INODE,3)
       RTHETAD=RTHETAD+YP(INODE)*SCAL(INODE,1,ICS6)*AREA(INODE,2)
           XRD=XRD+YP(INODE)*SCAL(INODE,1,ICS7)*AREA(INODE,1)
       XTHETAD=XTHETAD+YP(INODE)*SCAL(INODE,1,ICS5)*AREA(INODE,1)
```

```
C
 150      CONTINUE
C
         TROTOR=TNET
         TFIA=(FIANEW-FIAOLD)/DT
         TFIB=(FIBNEW-FIBOLD)/DT
C
        ENDIF
C
C
        IF (NITER.EQ.IUSRITER) THEN
C-------TO FIND OUT THE FLUID MOMENTUM FLUX ACROSS THE PART OF THE DOMAIN
C
C---- SET BLOCKN TO BE BLOCK1 TO BLOCK11
       USRDOM(1)='BLOCK-NUMBER-1'
       USRDOM(2)='BLOCK-NUMBER-2'
       USRDOM(3)='BLOCK-NUMBER-3'
       USRDOM(4)='BLOCK-NUMBER-4'
       USRDOM(5)='BLOCK-NUMBER-5'
       USRDOM(6)='BLOCK-NUMBER-6'
       USRDOM(7)='BLOCK-NUMBER-8'
       USRDOM(8)='BLOCK-NUMBER-9'
       USRDOM(9)='BLOCK-NUMBER-10'
C
       DO 151 DOMAINN=1,9
       CALL IPREC(USRDOM(DOMAINN),'BLOCK','CENTRES',IPT,
      +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
         DO 152 I=1,ILEN
           DO 153 J=1,JLEN
            DO 154 K=1,KLEN
             INODE=IP(I,J,K)
C
         WABS = W(INODE,1)+YP(INODE)*WNEW
         FIANEWP = FIANEWP+DEN(INODE,1)*YP(INODE)*WABS*VOL(INODE)
         FIBNEWP = FIBNEWP+DEN(INODE,1)*YP(INODE)*W(INODE,1)*VOL(INODE)
C
         THETAXP=THETAXP+YP(INODE)*SCAL(INODE,1,ICS5)*AREA(INODE,3)
         RTHETAP=RTHETAP+YP(INODE)*SCAL(INODE,1,ICS6)*AREA(INODE,2)
             XRP=XRP+YP(INODE)*SCAL(INODE,1,ICS7)*AREA(INODE,1)
         XTHETAP=XTHETAP+YP(INODE)*SCAL(INODE,1,ICS5)*AREA(INODE,1)
C
 154       CONTINUE
 153       CONTINUE
 152       CONTINUE
 151       CONTINUE
C
       CALL IPREC('BLOCK-NUMBER-7','BLOCK','CENTRES',IPT,
      +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
          DO 155 I=14,ILEN
           DO 156 J=1,JLEN
            DO 157 K=1,KLEN
             INODE=IP(I,J,K)
C
          WABS = W(INODE,1)+YP(INODE)*WNEW
          FIANEWP = FIANEWP+DEN(INODE,1)*YP(INODE)*WABS*VOL(INODE)
          FIBNEWP = FIBNEWP+DEN(INODE,1)*YP(INODE)*W(INODE,1)*VOL(INODE)
C
         THETAXP=THETAXP+YP(INODE)*SCAL(INODE,1,ICS5)*AREA(INODE,3)
         RTHETAP=RTHETAP+YP(INODE)*SCAL(INODE,1,ICS6)*AREA(INODE,2)
             XRP=XRP+YP(INODE)*SCAL(INODE,1,ICS7)*AREA(INODE,1)
         XTHETAP=XTHETAP+YP(INODE)*SCAL(INODE,1,ICS5)*AREA(INODE,1)
C
 157       CONTINUE
 156       CONTINUE
 155       CONTINUE
C
       CALL IPREC('BLOCK-NUMBER-11','BLOCK','CENTRES',IPT,
      +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
          DO 158 I=1,2
           DO 159 J=1,JLEN
```

```
            DO 160 K=1,KLEN
             INODE=IP(I,J,K)
C
          WABS = W(INODE,1)+YP(INODE)*WNEW
          FIANEWP = FIANEWP+DEN(INODE,1)*YP(INODE)*WABS*VOL(INODE)
          FIBNEWP = FIBNEWP+DEN(INODE,1)*YP(INODE)*W(INODE,1)*VOL(INODE)
C
         THETAXP=THETAXP+YP(INODE)*SCAL(INODE,1,ICS5)*AREA(INODE,3)
         RTHETAP=RTHETAP+YP(INODE)*SCAL(INODE,1,ICS6)*AREA(INODE,2)
             XRP=XRP+YP(INODE)*SCAL(INODE,1,ICS7)*AREA(INODE,1)
         XTHETAP=XTHETAP+YP(INODE)*SCAL(INODE,1,ICS5)*AREA(INODE,1)
C
 160       CONTINUE
 159       CONTINUE
 158       CONTINUE
C
          TFIAP=(FIANEWP-FIAOLDP)/DT
          TFIBP=(FIBNEWP-FIBOLDP)/DT
C
C------TO FIND THE RESIDUALS OF THE ANGULAR MOMENTUM EQUATION

C
C234567891123456789212345678931234567894123456789512345678961233456789712
         WRITE(ITXT,906)KSTEP,NITER,WNEW,ACCE,WOLD,DT,UNEW,UOLD,TIME,
     +        MOINA,MOINB,MOINC,MOIND,MOOUTA,MOOUTB,
     +        FIANEW,FIAOLD,FIBNEW,FIBOLD,
     +        TROTOR,TFIA,TFIB,TFRIC,MASSIA,MASSIC,MASSO,
     +        THETAXO,RTHETAO,XRO,XTHETAO,
     +        THETAXD,RTHETAD,XRD,XTHETAD,TSUM,
     +        MOOUTC,MOOUTD,FIANEWP,FIAOLDP,FIBNEWP,FIBOLDP,TFIAP,TFIBP,
     +        THETAXJ,RTHETAJ,XRJ,XTHETAJ,THETAXP,RTHETAP,XRP,XTHETAP
 906      FORMAT(I4,2X,I2,49(2X,E17.10))
         ENDIF
C
C
C
        RETURN
        END
```

D.3 USRBF

```
      SUBROUTINE USRBF (IPHASE,BX,BY,BZ,BPX,BPY,BPZ
     +                 ,U,V,W,P,VFRAC,DEN,VIS,TE,ED,RS,T,H,RF,SCAL
     +                 ,XP,YP,ZP,VOL,AREA,VPOR,ARPOR,WFACT,IPT
     +                 ,IBLK,IPVERT,IPNODN,IPFACN,IPNODF,IPNODB,IPFACB

     +                 ,WORK,IWORK,CWORK)
C
C***********************************************************************
C
C   UTILITY SUBROUTINE FOR USER-SUPPLIED BODY FORCES
C
C   >>> IMPORTANT                                                   <<<
C   >>>                                                            <<<
C   >>> USERS MAY ONLY ADD OR ALTER PARTS OF THE SUBROUTINE WITHIN  <<<
C   >>> THE DESIGNATED USER AREAS                                  <<<
C
C***********************************************************************
C
C   THIS SUBROUTINE IS CALLED BY THE FOLLOWING SUBROUTINES
C      BFCAL
C
C***********************************************************************
C   CREATED
C      24/01/92  ADB
C   MODIFIED
C      03/06/92  PHA  ADD PRECISION FLAG AND CHANGE IVERS TO 2
C      23/11/93  CSH  EXPLICITLY DIMENSION IPVERT ETC.
C      03/02/94  PHA  CHANGE FLOW3D TO CFDS-FLOW3D
C      03/03/94  FHW  CORRECTION OF SPELLING MISTAKE
C      23/03/94  FHW  EXAMPLES COMMENTED OUT
C      09/08/94  NSW  CORRECT SPELLING
C                     MOVE 'IF(IUSED.EQ.0) RETURN' OUT OF USER AREA
C      19/12/94  NSW  CHANGE FOR CFX-F3D
C      31/01/97  NSW  EXPLAIN USAGE IN MULTIPHASE FLOWS
C      02/07/97  NSW  UPDATE FOR CFX-4

C
C***********************************************************************
C
C   SUBROUTINE ARGUMENTS
C
C     IPHASE - PHASE NUMBER
C
C   * BX     - X-COMPONENT OF VELOCITY-INDEPENDENT BODY FORCE
C   * BY     - Y-COMPONENT OF VELOCITY-INDEPENDENT BODY FORCE
C   * BZ     - Z-COMPONENT OF VELOCITY-INDEPENDENT BODY FORCE
C   * BPX    -
C   * BPY    - COMPONENTS OF LINEARISABLE BODY FORCES.
C   * BPZ    -
C
C  N.B. TOTAL BODY-FORCE IS GIVEN BY:
C
C         X-COMPONENT = BX + BPX*U
C         Y-COMPONENT = BY + BPY*V
C         Z-COMPONENT = BZ + BPZ*W
C
C     U       - U COMPONENT OF VELOCITY
C     V       - V COMPONENT OF VELOCITY
C     W       - W COMPONENT OF VELOCITY
C     P       - PRESSURE
C     VFRAC   - VOLUME FRACTION
C     DEN     - DENSITY OF FLUID
C     VIS     - VISCOSITY OF FLUID
C     TE      - TURBULENT KINETIC ENERGY
C     ED      - EPSILON
C     RS      - REYNOLD STRESSES
C     T       - TEMPERATURE
C     H       - ENTHALPY
C     SCAL    - SCALARS (THE FIRST 'NCONC' OF THESE ARE MASS FRACTIONS)
C     XP      - X COORDINATES OF CELL CENTRES
C     YP      - Y COORDINATES OF CELL CENTRES
C     ZP      - Z COORDINATES OF CELL CENTRES
```

```
C       VOL     - VOLUME OF CELLS
C       AREA    - AREA OF CELLS
C       VPOR    - POROUS VOLUME
C       ARPOR   - POROUS AREA
C       WFACT   - WEIGHT FACTORS
C
C       IPT     - 1D POINTER ARRAY
C       IBLK    - BLOCK SIZE INFORMATION
C       IPVERT  - POINTER FROM CELL CENTERS TO 8 NEIGHBOURING VERTICES
C       IPNODN  - POINTER FROM CELL CENTERS TO 6 NEIGHBOURING CELLS
C       IPFACN  - POINTER FROM CELL CENTERS TO 6 NEIGHBOURING FACES
C       IPNODF  - POINTER FROM CELL FACES TO 2 NEIGHBOURING CELL CENTERS
C       IPNODB  - POINTER FROM BOUNDARY CENTERS TO CELL CENTERS
C       IPFACB  - POINTER FROM BOUNDARY CENTERS TO BOUNDARY FACESS
C
C       WORK    - REAL WORKSPACE ARRAY
C       IWORK   - INTEGER WORKSPACE ARRAY
C       CWORK   - CHARACTER WORKSPACE ARRAY
C
C    SUBROUTINE ARGUMENTS PRECEDED WITH A '*' ARE ARGUMENTS THAT MUST
C    BE SET  BY THE USER IN THIS ROUTINE.
C

C    NOTE THAT OTHER DATA MAY BE OBTAINED FROM CFX-4 USING THE
C    ROUTINE GETADD, FOR FURTHER DETAILS SEE THE VERSION 4
C    USER MANUAL.
C
C*************************************************************************
C
      LOGICAL LDEN,LVIS,LTURB,LTEMP,LBUOY,LSCAL,LCOMP
     +       ,LRECT,LCYN,LAXIS,LPOROS,LTRANS
C
      CHARACTER*(*) CWORK
C
C+++++++++++++++++ USER AREA 1 ++++++++++++++++++++++++++++++++++++++++
C---- AREA FOR USERS EXPLICITLY DECLARED VARIABLES
      REAL TSUM,INERTIA,ACCE,AREAM,WOLD,WTEMP,WNEW,UOLD,UNEW,WABS,
     +     WVSUM,VSUM,DELTAR,TNET,
     +     AMP,FREQ,PERIOD,OMEGA,REMAIN,PHASE,RADIAN,PULSE,
     +     MOINA,MOINB,MOINC,MOIND,MOOUTA,MOOUTB,MOOUTC,MOOUTD,
     +     FIAOLD,FIANEW,FIBOLD,FIBNEW,FIAOLDP,FIANEWP,FIBOLDP,FIBNEWP,
     +     TROTOR,TFIA,TFIB,TFIAP,TFIBP,TFRIC,MASSIA,MASSIC,MASSO,
     +     THETAXO,RTHETAO,XRO,XTHETAO,
     +     THETAXJ,RTHETAJ,XRJ,XTHETAJ,
     +     THETAXD,RTHETAD,XRD,XTHETAD,
     +     THETAXP,RTHETAP,XRP,XTHETAP
      INTEGER ITXT,ISEQF
C
C+++++++++++++++++ END OF USER AREA 1 ++++++++++++++++++++++++++++++++++
C
      COMMON
     + /ALL/     NBLOCK,NCELL,NBDRY,NNODE,NFACE,NVERT,NDIM
     + /ALLWRK/  NRWS,NIWS,NCWS,IWRFRE,IWIFRE,IWCFRE
     + /ADDIMS/  NPHASE,NSCAL,NVAR,NPROP
     +          ,NDVAR,NDPROP,NDXNN,NDGEOM,NDCOEF,NILIST,NRLIST,NTOPOL
     + /CHKUSR/  IVERS,IUCALL,IUSED
     + /DEVICE/  NREAD,NWRITE,NRDISK,NWDISK
     + /IDUM/    ILEN,JLEN
     + /LOGIC/   LDEN,LVIS,LTURB,LTEMP,LBUOY,LSCAL,LCOMP
     +          ,LRECT,LCYN,LAXIS,LPOROS,LTRANS
     + /MLTGRD/  MLEVEL,NLEVEL,ILEVEL
     + /SGLDBL/  IFLGPR,ICHKPR
     + /SPARM/   SMALL,SORMAX,NITER,INDPRI,MAXIT,NODREF,NODMON
     + /TIMUSR/  DTUSR
     + /TRANSI/  NSTEP,KSTEP,MF,INCORE
     + /TRANSR/  TIME,DT,DTINVF,TPARM
C
C+++++++++++++++++ USER AREA 2 ++++++++++++++++++++++++++++++++++++++++
C---- AREA FOR USERS TO DECLARE THEIR OWN COMMON BLOCKS
C     THESE SHOULD START WITH THE CHARACTERS 'UC' TO ENSURE
C     NO CONFLICT WITH NON-USER COMMON BLOCKS
      COMMON
     +  /UC1/ TSUM,INERTIA,ACCE,AREAM,WOLD,WTEMP,WNEW,UOLD,UNEW,WABS,
     +     WVSUM,VSUM,DELTAR,TNET,
     +     AMP,FREQ,PERIOD,OMEGA,REMAIN,PHASE,RADIAN,PULSE,
     +     MOINA,MOINB,MOINC,MOIND,MOOUTA,MOOUTB,MOOUTC,MOOUTD,
```

```
     +      FIAOLD,FIANEW,FIBOLD,FIBNEW,FIAOLDP,FIANEWP,FIBOLDP,FIBNEWP,
     +      TROTOR,TFIA,TFIB,TFIAP,TFIBP,TFRIC,MASSIA,MASSIC,MASSO,
     +      THETAXO,RTHETAO,XRO,XTHETAO,
     +      THETAXJ,RTHETAJ,XRJ,XTHETAJ,
     +      THETAXD,RTHETAD,XRD,XTHETAD,
     +      THETAXP,RTHETAP,XRP,XTHETAP
C
C+++++++++++++++++ END OF USER AREA 2 ++++++++++++++++++++++++++++++++++
C
      DIMENSION BX(NCELL),BY(NCELL),BZ(NCELL)
     +,BPX(NCELL),BPY(NCELL),BPZ(NCELL)
C
      DIMENSION
     + U(NNODE,NPHASE),V(NNODE,NPHASE),W(NNODE,NPHASE),P(NNODE,NPHASE)
     +,VFRAC(NNODE,NPHASE),DEN(NNODE,NPHASE),VIS(NNODE,NPHASE)
     +,TE(NNODE,NPHASE),ED(NNODE,NPHASE),RS(NNODE,NPHASE,*)
     +,T(NNODE,NPHASE),H(NNODE,NPHASE),RF(NNODE,NPHASE,4)
     +,SCAL(NNODE,NPHASE,NSCAL)
C
      DIMENSION
     + XP(NNODE),YP(NNODE),ZP(NNODE)
     +,VOL(NCELL),AREA(NFACE,3),VPOR(NCELL),ARPOR(NFACE,3)
     +,WFACT(NFACE)
     +,IPT(*),IBLK(5,NBLOCK)
     +,IPVERT(NCELL,8),IPNODN(NCELL,6),IPFACN(NCELL,6),IPNODF(NFACE,4)
     +,IPNODB(NBDRY,4),IPFACB(NBDRY)
     +,IWORK(*),WORK(*),CWORK(*)
C
C+++++++++++++++++ USER AREA 3 ++++++++++++++++++++++++++++++++++++++++
C---- AREA FOR USERS TO DIMENSION THEIR ARRAYS
C
C---- AREA FOR USERS TO DEFINE DATA STATEMENTS
C
C+++++++++++++++++ END OF USER AREA 3 ++++++++++++++++++++++++++++++++++
C
C---- STATEMENT FUNCTION FOR ADDRESSING
      IP(I,J,K) = IPT( (K-1)*ILEN*JLEN + (J-1)*ILEN + I )
C
C----VERSION NUMBER OF USER ROUTINE AND PRECISION FLAG
C
      IVERS=2
      ICHKPR = 1
C

C+++++++++++++++++ USER AREA 4 ++++++++++++++++++++++++++++++++++++++++
C---- TO USE THIS USER ROUTINE FIRST SET IUSED=1
C
       IUSED=1
C
C+++++++++++++++++ END OF USER AREA 4 ++++++++++++++++++++++++++++++++++
C
       IF (IUSED.EQ.0) RETURN
C
C---- FRONTEND CHECKING OF USER ROUTINE
       IF (IUCALL.EQ.0) RETURN
C
C+++++++++++++++++ USER AREA 5 ++++++++++++++++++++++++++++++++++++++++
C
C  THIS ROUTINE IS ENTERED REPEATEDLY FOR EACH PHASE IN A MULTIPHASE
C  CALCULATION. BODY FORCES CAN BE SET FOR A PARTICULAR PHASE USING
C  THE VARIABLE IPHASE. EG. IF (IPHASE.EQ.2) WOULD ALLOW BODY FORCES
C  FOR THE SECOND PHASE.
       IPHASE=1
C
      IF ((NITER.EQ.9).AND.(KSTEP.EQ.1)) THEN
      OPEN (UNIT=49, FILE='bf.txt',STATUS='NEW')
       ISEQF=0
        ITXT=49
        CALL FILCON('USRBF','bf.txt','OPEN','FORMATTED',
     +             'NEW',ITXT,ISEQF,IOST,IERR)
C
        IF (IERR.NE.0) THEN
        CALL FILERR('USRBF','bf.txt','OPEN','NEW',
     +               ITXT,ISEQF,IOST,IERR)
       ENDIF
      ENDIF
```

```
C
C---- ADD USER-DEFINED BODY FORCES.
C---- USE IPALL TO FIND 1D ADDRESS OF ALL CELL CENTRES
C
      CALL IPALL('*','*','BLOCK','CENTRES',IPT,NPT,CWORK,IWORK)
C
        DO 104 I=1,NPT
               INODE=IPT(I)
C
        BY(INODE) = BY(INODE)+(DEN(INODE,1)*2*WNEW*W(INODE,1))+
     +     (YP(INODE)*WNEW*WNEW*DEN(INODE,1))
C
        BZ(INODE) = BZ(INODE)-(DEN(INODE,1)*2*WNEW*V(INODE,1))-
     +      (YP(INODE)*ACCE*DEN(INODE,1))
 104     CONTINUE
C234567891123456789212345678931234567894123456789512345678961233456789712
C
       IF (NITER.EQ.9) THEN
       WRITE(49,907)KSTEP,NITER,BY(INODE),BZ(INODE)
 907    FORMAT(I4,2X,I2,2(2X,E17.10))
       ENDIF
C
C+++++++++++++++++ END OF USER AREA 5 +++++++++++++++++++++++++++++++++++
C
      RETURN
      END
```

D.4 USRGRD

```
      SUBROUTINE USRGRD(U,V,W,P,VFRAC,DEN,VIS,TE,ED,RS,T,H,RF,SCAL,
     +                  XP,YP,ZP,VOL,AREA,VPOR,ARPOR,WFACT,
     +                  XCOLD,YCOLD,ZCOLD,XC,YC,ZC,IPT,
     +                  IBLK,IPVERT,IPNODN,IPFACN,IPNODF,IPNODB,IPFACB,
     +                  WORK,IWORK,CWORK)
C
C***********************************************************************
C
C   USER SUBROUTINE TO ALLOW USERS TO GENERATE A GRID FOR CFX-F3D
C
C   >>> IMPORTANT                                                   <<<
C   >>> USERS MAY ONLY ADD OR ALTER PARTS OF THE SUBROUTINE WITHIN  <<<
C   >>> THE DESIGNATED USER AREAS                                   <<<
C
C***********************************************************************
C
C   THIS SUBROUTINE IS CALLED BY THE FOLLOWING SUBROUTINES
C      CREATE  CUSR
C
C***********************************************************************
C   CREATED
C      27/04/90  ADB
C   MODIFIED
C      05/08/91  IRH  NEW STRUCTURE
C      09/09/91  IRH  CORRECT EXAMPLE
C      01/10/91  DSC  REDUCE COMMENT LINE GOING OVER 72 COLUMNS.
C      29/11/91  PHA  UPDATE CALLED BY COMMENT, ADD RF ARGUMENT,
C                     CHANGE LAST DIMENSION OF RS TO 6 AND IVERS TO 2
C      03/06/92  PHA  ADD PRECISION FLAG AND CHANGE IVERS TO 3
C      03/07/92  DSC  CORRECT COMMON MLTGRD.
C      23/11/93  CSH  EXPLICITLY DIMENSION IPVERT ETC.
C      03/02/94  PHA  CHANGE FLOW3D TO CFDS-FLOW3D
C      03/03/94  FHW  CORRECTION OF SPELLING MISTAKE
C      22/08/94  NSW  MOVE 'IF(IUSED.EQ.0) RETURN' OUT OF USER AREA
C      19/12/94  NSW  CHANGE FOR CFX-F3D
C
C***********************************************************************
C
C   SUBROUTINE ARGUMENTS
C
C      U       - U COMPONENT OF VELOCITY
C      V       - V COMPONENT OF VELOCITY
C      W       - W COMPONENT OF VELOCITY
C      P       - PRESSURE
C      VFRAC   - VOLUME FRACTION
C      DEN     - DENSITY OF FLUID
C      VIS     - VISCOSITY OF FLUID
C      TE      - TURBULENT KINETIC ENERGY
C      ED      - EPSILON
C      RS      - REYNOLD STRESSES
C      T       - TEMPERATURE
C      H       - ENTHALPY
C      RF      - REYNOLD FLUXES
C      SCAL    - SCALARS (THE FIRST 'NCONC' OF THESE ARE MASS FRACTIONS)
C      XP      - X COORDINATES OF CELL CENTRES
C      YP      - Y COORDINATES OF CELL CENTRES
C      ZP      - Z COORDINATES OF CELL CENTRES
C      VOL     - VOLUME OF CELLS
C      AREA    - AREA OF CELLS
C      VPOR    - POROUS VOLUME
C      ARPOR   - POROUS AREA
C      WFACT   - WEIGHT FACTORS
C   *  XC      - X COORDINATES OF CELL VERTICES
C   *  YC      - Y COORDINATES OF CELL VERTICES
C   *  ZC      - Z COORDINATES OF CELL VERTICES
C      XCOLD   - X COORDINATES OF CELL VERTICES AT START OF TIME STEP
C      YCOLD   - Y COORDINATES OF CELL VERTICES AT START OF TIME STEP
C      ZCOLD   - Z COORDINATES OF CELL VERTICES AT START OF TIME STEP
C
C      IPT     - 1D POINTER ARRAY
C      IBLK    - BLOCK SIZE INFORMATION
```

```
C      IPVERT - POINTER FROM CELL CENTERS TO 8 NEIGHBOURING VERTICES
C      IPNODN - POINTER FROM CELL CENTERS TO 6 NEIGHBOURING CELLS
C      IPFACN - POINTER FROM CELL CENTERS TO 6 NEIGHBOURING FACES
C      IPNODF - POINTER FROM CELL FACES TO 2 NEIGHBOURING CELL CENTERS
C      IPNODB - POINTER FROM BOUNDARY CENTERS TO CELL CENTERS
C      IPFACB - POINTER FROM BOUNDARY CENTERS TO BOUNDARY FACESS
C
C      WORK   - REAL WORKSPACE ARRAY
C      IWORK  - INTEGER WORKSPACE ARRAY
C      CWORK  - CHARACTER WORKSPACE ARRAY
C
C    SUBROUTINE ARGUMENTS PRECEDED WITH A '*' ARE ARGUMENTS THAT MUST
C    BE SET  BY THE USER IN THIS ROUTINE.
C
C    NOTE THAT OTHER DATA MAY BE OBTAINED FROM CFX-F3D USING THE
C    ROUTINE GETADD, FOR FURTHER DETAILS SEE THE VERSION 4
C    USER MANUAL.
C
C*************************************************************************
C
      LOGICAL LDEN,LVIS,LTURB,LTEMP,LBUOY,LSCAL,LCOMP
     +       ,LRECT,LCYN,LAXIS,LPOROS,LTRANS
C
      CHARACTER*(*) CWORK
C
C+++++++++++++++++ USER AREA 1 +++++++++++++++++++++++++++++++++++++++++
C---- AREA FOR USERS EXPLICITLY DECLARED VARIABLES
C
C+++++++++++++++++ END OF USER AREA 1 +++++++++++++++++++++++++++++++++++
C
      COMMON
     + /ALL/     NBLOCK,NCELL,NBDRY,NNODE,NFACE,NVERT,NDIM
     + /ALLWRK/ NRWS,NIWS,NCWS,IWRFRE,IWIFRE,IWCFRE
     + /ADDIMS/ NPHASE,NSCAL,NVAR,NPROP
     +         ,NDVAR,NDPROP,NDXNN,NDGEOM,NDCOEF,NILIST,NRLIST,NTOPOL
     + /CHKUSR/ IVERS,IUCALL,IUSED
     + /CONC/    NCONC
     + /DEVICE/ NREAD,NWRITE,NRDISK,NWDISK
     + /IDUM/    ILEN,JLEN
     + /LOGIC/   LDEN,LVIS,LTURB,LTEMP,LBUOY,LSCAL,LCOMP
     +          ,LRECT,LCYN,LAXIS,LPOROS,LTRANS
     + /MLTGRD/ MLEVEL,NLEVEL,ILEVEL
     + /SGLDBL/ IFLGPR,ICHKPR
     + /SPARM/   SMALL,SORMAX,NITER,INDPRI,MAXIT,NODREF,NODMON
     + /TIMUSR/ DTUSR
     + /TRANSI/ NSTEP,KSTEP,MF,INCORE
     + /TRANSR/ TIME,DT,DTINVF,TPARM
C
C+++++++++++++++++ USER AREA 2 +++++++++++++++++++++++++++++++++++++++++
C---- AREA FOR USERS TO DECLARE THEIR OWN COMMON BLOCKS
C      THESE SHOULD START WITH THE CHARACTERS 'UC' TO ENSURE
C      NO CONFLICT WITH NON-USER COMMON BLOCKS
C
C+++++++++++++++++ END OF USER AREA 2 +++++++++++++++++++++++++++++++++++
C
      DIMENSION
     + U(NNODE,NPHASE),V(NNODE,NPHASE),W(NNODE,NPHASE),P(NNODE,NPHASE)
     +,VFRAC(NNODE,NPHASE),DEN(NNODE,NPHASE),VIS(NNODE,NPHASE)
     +,TE(NNODE,NPHASE),ED(NNODE,NPHASE),RS(NNODE,NPHASE,6)
     +,T(NNODE,NPHASE),H(NNODE,NPHASE),RF(NNODE,NPHASE,4)
     +,SCAL(NNODE,NPHASE,NSCAL)
      DIMENSION
     + XP(NNODE),YP(NNODE),ZP(NNODE),XC(NVERT),YC(NVERT),ZC(NVERT)
     +,XCOLD(NVERT),YCOLD(NVERT),ZCOLD(NVERT)
     +,VOL(NCELL),AREA(NFACE,3),VPOR(NCELL),ARPOR(NFACE,3)
     +,WFACT(NFACE)
     +,IPT(*),IBLK(5,NBLOCK)
     +,IPVERT(NCELL,8),IPNODN(NCELL,6),IPFACN(NCELL,6),IPNODF(NFACE,4)
     +,IPNODB(NBDRY,4),IPFACB(NBDRY)
     +,IWORK(*),WORK(*),CWORK(*)
C
C+++++++++++++++++ USER AREA 3 +++++++++++++++++++++++++++++++++++++++++
C---- AREA FOR USERS TO DIMENSION THEIR ARRAYS
C
C---- AREA FOR USERS TO DEFINE DATA STATEMENTS
C
```

```
C+++++++++++++++++ END OF USER AREA 3 ++++++++++++++++++++++++++++++++++
C
C---- STATEMENT FUNCTION FOR ADDRESSING
      IP(I,J,K)=IPT((K-1)*ILEN*JLEN+(J-1)*ILEN+I)
C
C---- VERSION NUMBER OF USER ROUTINE AND PRECISION FLAG
C
      IVERS=3
      ICHKPR = 1
C
C+++++++++++++++++ USER AREA 4 ++++++++++++++++++++++++++++++++++++++++++
C---- TO USE THIS USER ROUTINE FIRST SET IUSED=1
C
       IUSED=1
C
C+++++++++++++++++ END OF USER AREA 4 ++++++++++++++++++++++++++++++++++
C
       IF (IUSED.EQ.0) RETURN
C
C---- FRONTEND CHECKING OF USER ROUTINE
       IF (IUCALL.EQ.0) RETURN
C
C+++++++++++++++++ USER AREA 5 ++++++++++++++++++++++++++++++++++++++++++
C
      IF (KSTEP.EQ.0) THEN
C
C---- SPECIAL VERSION TO CONVERT A CARTESIAN GRID INTO
C     A CYLINDRICAL GRID
C
C     CARTESIAN    CYLINDRICAL
C        X          X
C        Y      \
C                   R AND THETA
C        Z      /
C
C NOTE
C
C     IF R = 0.0 ONLY ON THE EDGE OF A BLOCK
C     YOU SHOULD NOT USE THE KEYWORDS 'AXIS INCLUDED'
C                 ---
C
C DEFINE A SMALL RADIUS LARGER THAN 1.0E-6
C
      SMALLR=1.0E-4
C
C---- INITIAL CONVERSION
C
      DO 10 I=1,NVERT
        R=SQRT(YC(I)**2+ZC(I)**2)
        IF (R.LE.SMALLR) THEN
          IF (.NOT.LAXIS) THEN
            R=SMALLR
          ENDIF
          THETA=0.0
        ELSE
          THETA=ATAN2(-ZC(I),YC(I))
        ENDIF
        YC(I)=R
        ZC(I)=THETA
 10   CONTINUE
C
C---- CORRECTION OF THETA AT R=0.0
C
      DO 100 IBLOCK=1,NBLOCK
         NI1=IBLK(1,IBLOCK)+1
         NJ1=IBLK(2,IBLOCK)+1
         NK1=IBLK(3,IBLOCK)+1
         IPVBLK=IBLK(5,IBLOCK)
         DO 110 K=2,NK1-1
           DO 120 J=2,NJ1-1
             DO 130 I=2,NI1-1
             IVERT=IPVBLK-1+(K-1)*NI1*NJ1+(J-1)*NI1+I
             R=YC(IVERT)
             IF (R.LE.SMALLR*1.0001) THEN
               IF (LAXIS) THEN
C AS AXIS MUST LIE ON LOW J FACE TAKE THETA FROM
```

```
C ANGLE OF NEXT VERTEX AWAY FROM AXIS
                  THETA=ZC(IVERT+NI1)
                ELSE
C TAKE THETA TO BE THE AVERAGE VALUE OF THE NEIGHBOURING
C INTERIOR VERTICES WHICH HAVE R > 1.0E-6
                  I1=IVERT+1
                  I2=IVERT+NI1
                  I3=IVERT+NI1*NJ1
                  I4=IVERT-1
                  I5=IVERT-NI1
                  I6=IVERT-NI1*NJ1
                  A1=1.0
                  A2=1.0
                  A3=1.0
                  A4=1.0
                  A5=1.0
                  A6=1.0
                  IF (I.EQ.NI1-1) A1=0.0
                  IF (J.EQ.NJ1-1) A2=0.0
                  IF (K.EQ.NK1-1) A3=0.0
                  IF (I.EQ.2)   A4=0.0
                  IF (J.EQ.2)   A5=0.0
                  IF (K.EQ.2)   A6=0.0
                  IF (YC(I1).LE.SMALLR*1.0001) A1=0.0
                  IF (YC(I2).LE.SMALLR*1.0001) A2=0.0
                  IF (YC(I3).LE.SMALLR*1.0001) A3=0.0
                  IF (YC(I4).LE.SMALLR*1.0001) A4=0.0
                  IF (YC(I5).LE.SMALLR*1.0001) A5=0.0
                  IF (YC(I6).LE.SMALLR*1.0001) A6=0.0
                  ASUM=A1+A2+A3+A4+A5+A6

                  THETA=(A1*ZC(I1)+A2*ZC(I2)+A3*ZC(I3)+
     +                   A4*ZC(I4)+A5*ZC(I5)+A6*ZC(I6))/ASUM
                ENDIF
                ZC(IVERT)=THETA
              ENDIF
  130         CONTINUE
  120       CONTINUE
  110     CONTINUE
  100   CONTINUE
C
        END IF
C
C+++++++++++++++++ END OF USER AREA 5 +++++++++++++++++++++++++++++++++++
C
        RETURN
        END
```

D.5 USRTRN

```
      SUBROUTINE USRTRN(U,V,W,P,VFRAC,DEN,VIS,TE,ED,RS,T,H,RF,SCAL,
     +                  XP,YP,ZP,VOL,AREA,VPOR,ARPOR,WFACT,CONV,IPT,
     +                  IBLK,IPVERT,IPNODN,IPFACN,IPNODF,IPNODB,IPFACB,
     +                  WORK,IWORK,CWORK)
C
C*****************************************************************
C
C   USER SUBROUTINE TO ALLOW USERS TO MODIFY OR MONITOR THE SOLUTION AT
C   THE END OF EACH TIME STEP
C   THIS SUBROUTINE IS CALLED BEFORE THE START OF THE RUN AS WELL AS AT
C   THE END OF EACH TIME STEP
C
C   >>> IMPORTANT                                                  <<<
C   >>>                                                           <<<
C   >>> USERS MAY ONLY ADD OR ALTER PARTS OF THE SUBROUTINE WITHIN  <<<
C   >>> THE DESIGNATED USER AREAS                                  <<<
C
C*****************************************************************
C
C   THIS SUBROUTINE IS CALLED BY THE FOLLOWING SUBROUTINES
C      CUSR  TRNMOD
C
C*****************************************************************
C   CREATED
C      27/04/90  ADB
C   MODIFIED
C      05/08/91  IRH  NEW STRUCTURE
C      01/10/91  DSC  REDUCE COMMENT LINE GOING OVER COLUMN 72.
C      29/11/91  PHA  UPDATE CALLED BY COMMENT, ADD RF ARGUMENT,
C                     CHANGE LAST DIMENSION OF RS TO 6 AND IVERS TO 2
C      05/06/92  PHA  ADD PRECISION FLAG AND CHANGE IVERS TO 3
C      03/07/92  DSC  CORRECT COMMON MLTGRD.
C      23/11/93  CSH  EXPLICITLY DIMENSION IPVERT ETC.
C      03/02/94  PHA  CHANGE FLOW3D TO CFDS-FLOW3D
C      22/08/94  NSW  MOVE 'IF(IUSED.EQ.0) RETURN' OUT OF USER AREA
C      19/12/94  NSW  CHANGE FOR CFX-F3D
C      02/07/97  NSW  UPDATE FOR CFX-4
C
C*****************************************************************
C
C   SUBROUTINE ARGUMENTS
C
C      U       - U COMPONENT OF VELOCITY
C      V       - V COMPONENT OF VELOCITY
C      W       - W COMPONENT OF VELOCITY
C      P       - PRESSURE
C      VFRAC   - VOLUME FRACTION
C      DEN     - DENSITY OF FLUID
C      VIS     - VISCOSITY OF FLUID
C      TE      - TURBULENT KINETIC ENERGY
C      ED      - EPSILON
C      RS      - REYNOLD STRESSES
C      T       - TEMPERATURE
C      H       - ENTHALPY
C      RF      - REYNOLD FLUXES
C      SCAL    - SCALARS (THE FIRST 'NCONC' OF THESE ARE MASS FRACTIONS)
C      XP      - X COORDINATES OF CELL CENTRES
C      YP      - Y COORDINATES OF CELL CENTRES
C      ZP      - Z COORDINATES OF CELL CENTRES
C      VOL     - VOLUME OF CELLS
C      AREA    - AREA OF CELLS
C      VPOR    - POROUS VOLUME
C      ARPOR   - POROUS AREA
C      WFACT   - WEIGHT FACTORS
C      CONV    - CONVECTION COEFFICIENTS
C
C      IPT     - 1D POINTER ARRAY
C      IBLK    - BLOCK SIZE INFORMATION
C      IPVERT  - POINTER FROM CELL CENTERS TO 8 NEIGHBOURING VERTICES
C      IPNODN  - POINTER FROM CELL CENTERS TO 6 NEIGHBOURING CELLS
C      IPFACN  - POINTER FROM CELL CENTERS TO 6 NEIGHBOURING FACES
C      IPNODF  - POINTER FROM CELL FACES TO 2 NEIGHBOURING CELL CENTERS
```

```
C      IPNODB - POINTER FROM BOUNDARY CENTERS TO CELL CENTERS
C      IPFACB - POINTER FROM BOUNDARY CENTERS TO BOUNDARY FACESS
C
C      WORK   - REAL WORKSPACE ARRAY
C      IWORK  - INTEGER WORKSPACE ARRAY
C      CWORK  - CHARACTER WORKSPACE ARRAY
C
C   SUBROUTINE ARGUMENTS PRECEDED WITH A '*' ARE ARGUMENTS THAT MUST
C   BE SET  BY THE USER IN THIS ROUTINE.
C
C   NOTE THAT OTHER DATA MAY BE OBTAINED FROM CFX-4 USING THE
C   ROUTINE GETADD, FOR FURTHER DETAILS SEE THE VERSION 4
C   USER MANUAL.
C
C*********************************************************************
C
C
      LOGICAL LDEN,LVIS,LTURB,LTEMP,LBUOY,LSCAL,LCOMP
     +       ,LRECT,LCYN,LAXIS,LPOROS,LTRANS
C
      CHARACTER*(*) CWORK
C
C+++++++++++++++++ USER AREA 1 ++++++++++++++++++++++++++++++++++++++++
C---- AREA FOR USERS EXPLICITLY DECLARED VARIABLES
C
      REAL TSUM,INERTIA,ACCE,AREAM,WOLD,WTEMP,WNEW,UOLD,UNEW,WABS,
     +     WVSUM,VSUM,DELTAR,TNET,
     +     AMP,FREQ,PERIOD,OMEGA,REMAIN,PHASE,RADIAN,PULSE,
     +     MOINA,MOINB,MOINC,MOIND,MOOUTA,MOOUTB,MOOUTC,MOOUTD,
     +     FIAOLD,FIANEW,FIBOLD,FIBNEW,FIAOLDP,FIANEWP,FIBOLDP,FIBNEWP,
     +     TROTOR,TFIA,TFIB,TFIAP,TFIBP,TFRIC,MASSIA,MASSIC,MASSO,
     +     THETAXO,RTHETAO,XRO,XTHETAO,
     +     THETAXJ,RTHETAJ,XRJ,XTHETAJ,
     +     THETAXD,RTHETAD,XRD,XTHETAD,
     +     THETAXP,RTHETAP,XRP,XTHETAP,UA,
     +     RELANG,ABSANG,MAF,
     +     SUMMF,SUMXP,SUMU,SUMW,SUMWABS,SUMRANG,SUMAANG,
     +     PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,AANGM,PLNRELM,PLNABSM
      INTEGER ITXT,ISEQF,DOMAINN
C
C+++++++++++++++++ END OF USER AREA 1 ++++++++++++++++++++++++++++++++++
C
      COMMON
     + /ALL/     NBLOCK,NCELL,NBDRY,NNODE,NFACE,NVERT,NDIM
     + /ALLWRK/ NRWS,NIWS,NCWS,IWRFRE,IWIFRE,IWCFRE
     + /ADDIMS/ NPHASE,NSCAL,NVAR,NPROP
     +          ,NDVAR,NDPROP,NDXNN,NDGEOM,NDCOEF,NILIST,NRLIST,NTOPOL
     + /CHKUSR/ IVERS,IUCALL,IUSED
     + /CONC/    NCONC
     + /DEVICE/ NREAD,NWRITE,NRDISK,NWDISK
     + /IDUM/    ILEN,JLEN
     + /LOGIC/   LDEN,LVIS,LTURB,LTEMP,LBUOY,LSCAL,LCOMP
     +          ,LRECT,LCYN,LAXIS,LPOROS,LTRANS
     + /MLTGRD/ MLEVEL,NLEVEL,ILEVEL
     + /SGLDBL/ IFLGPR,ICHKPR
     + /SPARM/   SMALL,SORMAX,NITER,INDPRI,MAXIT,NODREF,NODMON
     + /TIMUSR/ DTUSR
     + /TRANSI/ NSTEP,KSTEP,MF,INCORE
     + /TRANSR/ TIME,DT,DTINVF,TPARM
C
C+++++++++++++++++ USER AREA 2 ++++++++++++++++++++++++++++++++++++++++
C---- AREA FOR USERS TO DECLARE THEIR OWN COMMON BLOCKS
C      THESE SHOULD START WITH THE CHARACTERS 'UC' TO ENSURE
C      NO CONFLICT WITH NON-USER COMMON BLOCKS
       COMMON
     +   /UC1/ TSUM,INERTIA,ACCE,AREAM,WOLD,WTEMP,WNEW,UOLD,UNEW,WABS,
     +      WVSUM,VSUM,DELTAR,TNET,
     +      AMP,FREQ,PERIOD,OMEGA,REMAIN,PHASE,RADIAN,PULSE,
     +      MOINA,MOINB,MOINC,MOIND,MOOUTA,MOOUTB,MOOUTC,MOOUTD,
     +      FIAOLD,FIANEW,FIBOLD,FIBNEW,FIAOLDP,FIANEWP,FIBOLDP,FIBNEWP,
     +      TROTOR,TFIA,TFIB,TFIAP,TFIBP,TFRIC,MASSIA,MASSIC,MASSO,
     +      THETAXO,RTHETAO,XRO,XTHETAO,
     +      THETAXJ,RTHETAJ,XRJ,XTHETAJ,
     +      THETAXD,RTHETAD,XRD,XTHETAD,
     +      THETAXP,RTHETAP,XRP,XTHETAP,UA,
     +      RELANG,ABSANG,MAF,
```

```
     +      SUMMF,SUMXP,SUMU,SUMW,SUMWABS,SUMRANG,SUMAANG,
     +      PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,AANGM,PLNRELM,PLNABSM
C
C+++++++++++++++++ END OF USER AREA 2 ++++++++++++++++++++++++++++++++++
C
      DIMENSION
     + U(NNODE,NPHASE),V(NNODE,NPHASE),W(NNODE,NPHASE),P(NNODE,NPHASE)
     +,VFRAC(NNODE,NPHASE),DEN(NNODE,NPHASE),VIS(NNODE,NPHASE)
     +,TE(NNODE,NPHASE),ED(NNODE,NPHASE),RS(NNODE,NPHASE,6)
     +,T(NNODE,NPHASE),H(NNODE,NPHASE),RF(NNODE,NPHASE,4)
     +,SCAL(NNODE,NPHASE,NSCAL)
      DIMENSION
     + XP(NNODE),YP(NNODE),ZP(NNODE)
     +,VOL(NCELL),AREA(NFACE,3),VPOR(NCELL),ARPOR(NFACE,3)
     +,WFACT(NFACE),CONV(NFACE,NPHASE)
     +,IPT(*),IBLK(5,NBLOCK)
     +,IPVERT(NCELL,8),IPNODN(NCELL,6),IPFACN(NCELL,6),IPNODF(NFACE,4)
     +,IPNODB(NBDRY,4),IPFACB(NBDRY)
     +,IWORK(*),WORK(*),CWORK(*)
C
C+++++++++++++++++ USER AREA 3 ++++++++++++++++++++++++++++++++++++++++
C---- AREA FOR USERS TO DIMENSION THEIR ARRAYS
C
      CHARACTER *15 USRDOM
      DIMENSION USRDOM(0:11)
C---- AREA FOR USERS TO DEFINE DATA STATEMENTS
C
C+++++++++++++++++ END OF USER AREA 3 ++++++++++++++++++++++++++++++++++
C
C---- STATEMENT FUNCTION FOR ADDRESSING
      IP(I,J,K)=IPT((K-1)*ILEN*JLEN+(J-1)*ILEN+I)
C
C----VERSION NUMBER OF USER ROUTINE AND PRECISION FLAG
C
      IVERS=3
      ICHKPR = 1
C
C+++++++++++++++++ USER AREA 4 ++++++++++++++++++++++++++++++++++++++++
C---- TO USE THIS USER ROUTINE FIRST SET IUSED=1
C
       IUSED=1
C
C+++++++++++++++++ END OF USER AREA 4 ++++++++++++++++++++++++++++++++++
C
       IF (IUSED.EQ.0) RETURN
C
C---- FRONTEND CHECKING OF USER ROUTINE
       IF (IUCALL.EQ.0) RETURN
C
C+++++++++++++++++ USER AREA 5 ++++++++++++++++++++++++++++++++++++++++
C
         IPHASE=1
C----(SET TIME INCREMENT FOR NEXT TIME STEP)
C       IF (KSTEP.GE.0) THEN
C       DTUSR = 0.0000002
C       ENDIF
C
C       IF (KSTEP.GE.150) THEN
C       DTUSR = DT*1.035953352
C       ENDIF
C       IF (KSTEP.GE.300) THEN
C       DTUSR=0.00004
C       ENDIF
C
C        TO PRINT THE VARIABLES ON PLANES
        IF (KSTEP.EQ.40) THEN
        ITXT=69
        ISEQF=0
         CALL FILCON('USRTRN','data40.txt','OPEN','FORMATTED',
     +             'NEW',ITXT,ISEQF,IOST,IERR)
C
         IF (IERR.NE.0) THEN
         CALL FILERR('USRTRN','data40.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
       ENDIF
      ENDIF
```

```
      IF (KSTEP.EQ.400) THEN
      ITXT=50
      ISEQF=0
       CALL FILCON('USRTRN','data400.txt','OPEN','FORMATTED',
     +            'NEW',ITXT,ISEQF,IOST,IERR)
C
       IF (IERR.NE.0) THEN
       CALL FILERR('USRTRN','data400.txt','OPEN','NEW',
     +              ITXT,ISEQF,IOST,IERR)
      ENDIF
     ENDIF
      IF (KSTEP.EQ.420) THEN
      ITXT=51
      ISEQF=0
       CALL FILCON('USRTRN','data420.txt','OPEN','FORMATTED',
     +            'NEW',ITXT,ISEQF,IOST,IERR)
C
       IF (IERR.NE.0) THEN
       CALL FILERR('USRTRN','data420.txt','OPEN','NEW',
     +              ITXT,ISEQF,IOST,IERR)
      ENDIF
     ENDIF
      IF (KSTEP.EQ.440) THEN
      ITXT=52
      ISEQF=0
       CALL FILCON('USRTRN','data440.txt','OPEN','FORMATTED',
     +            'NEW',ITXT,ISEQF,IOST,IERR)
C
       IF (IERR.NE.0) THEN
       CALL FILERR('USRTRN','data440.txt','OPEN','NEW',
     +              ITXT,ISEQF,IOST,IERR)
      ENDIF
     ENDIF
      IF (KSTEP.EQ.460) THEN
      ITXT=53
      ISEQF=0
       CALL FILCON('USRTRN','data460.txt','OPEN','FORMATTED',
     +            'NEW',ITXT,ISEQF,IOST,IERR)
C
       IF (IERR.NE.0) THEN
       CALL FILERR('USRTRN','data460.txt','OPEN','NEW',
     +              ITXT,ISEQF,IOST,IERR)
      ENDIF
     ENDIF
      IF (KSTEP.EQ.480) THEN
      ITXT=54
      ISEQF=0
       CALL FILCON('USRTRN','data480.txt','OPEN','FORMATTED',
     +            'NEW',ITXT,ISEQF,IOST,IERR)
C
       IF (IERR.NE.0) THEN
       CALL FILERR('USRTRN','data480.txt','OPEN','NEW',
     +              ITXT,ISEQF,IOST,IERR)
      ENDIF
     ENDIF
      IF (KSTEP.EQ.500) THEN
      ITXT=55
      ISEQF=0
       CALL FILCON('USRTRN','data500.txt','OPEN','FORMATTED',
     +            'NEW',ITXT,ISEQF,IOST,IERR)
C
       IF (IERR.NE.0) THEN
       CALL FILERR('USRTRN','data500.txt','OPEN','NEW',
     +              ITXT,ISEQF,IOST,IERR)
      ENDIF
     ENDIF
      IF (KSTEP.EQ.520) THEN
      ITXT=56
      ISEQF=0
       CALL FILCON('USRTRN','data520.txt','OPEN','FORMATTED',
     +            'NEW',ITXT,ISEQF,IOST,IERR)
C
       IF (IERR.NE.0) THEN
       CALL FILERR('USRTRN','data520.txt','OPEN','NEW',
     +              ITXT,ISEQF,IOST,IERR)
      ENDIF
```

```
        ENDIF
         IF (KSTEP.EQ.540) THEN
         ITXT=57
         ISEQF=0
          CALL FILCON('USRTRN','data540.txt','OPEN','FORMATTED',
     +              'NEW',ITXT,ISEQF,IOST,IERR)
C
          IF (IERR.NE.0) THEN
          CALL FILERR('USRTRN','data540.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
         ENDIF
        ENDIF
         IF (KSTEP.EQ.560) THEN
         ITXT=58
         ISEQF=0
          CALL FILCON('USRTRN','data560.txt','OPEN','FORMATTED',
     +              'NEW',ITXT,ISEQF,IOST,IERR)
C
          IF (IERR.NE.0) THEN
          CALL FILERR('USRTRN','data560.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
         ENDIF
        ENDIF
         IF (KSTEP.EQ.580) THEN
         ITXT=59
         ISEQF=0
          CALL FILCON('USRTRN','data580.txt','OPEN','FORMATTED',
     +              'NEW',ITXT,ISEQF,IOST,IERR)
C
          IF (IERR.NE.0) THEN
          CALL FILERR('USRTRN','data580.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
         ENDIF
        ENDIF
         IF (KSTEP.EQ.600) THEN
         ITXT=60
         ISEQF=0
          CALL FILCON('USRTRN','data600.txt','OPEN','FORMATTED',
     +              'NEW',ITXT,ISEQF,IOST,IERR)
C
          IF (IERR.NE.0) THEN
          CALL FILERR('USRTRN','data600.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
         ENDIF
        ENDIF
         IF (KSTEP.EQ.620) THEN
         ITXT=61
         ISEQF=0
          CALL FILCON('USRTRN','data620.txt','OPEN','FORMATTED',
     +              'NEW',ITXT,ISEQF,IOST,IERR)
C
          IF (IERR.NE.0) THEN
          CALL FILERR('USRTRN','data620.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
         ENDIF
        ENDIF
         IF (KSTEP.EQ.640) THEN
         ITXT=62
         ISEQF=0
          CALL FILCON('USRTRN','data640.txt','OPEN','FORMATTED',
     +              'NEW',ITXT,ISEQF,IOST,IERR)
C
          IF (IERR.NE.0) THEN
          CALL FILERR('USRTRN','data640.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
         ENDIF
        ENDIF
         IF (KSTEP.EQ.660) THEN
         ITXT=63
         ISEQF=0
          CALL FILCON('USRTRN','data660.txt','OPEN','FORMATTED',
     +              'NEW',ITXT,ISEQF,IOST,IERR)

          IF (IERR.NE.0) THEN
          CALL FILERR('USRTRN','data660.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
```

```
        ENDIF
       ENDIF
        IF (KSTEP.EQ.680) THEN
        ITXT=64
        ISEQF=0
         CALL FILCON('USRTRN','data680.txt','OPEN','FORMATTED',
     +              'NEW',ITXT,ISEQF,IOST,IERR)

         IF (IERR.NE.0) THEN
         CALL FILERR('USRTRN','data680.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
        ENDIF
       ENDIF
C
        IF (KSTEP.EQ.700) THEN
        ITXT=65
        ISEQF=0
         CALL FILCON('USRTRN','data700.txt','OPEN','FORMATTED',
     +              'NEW',ITXT,ISEQF,IOST,IERR)

         IF (IERR.NE.0) THEN
         CALL FILERR('USRTRN','data700.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
        ENDIF
       ENDIF
        IF (KSTEP.EQ.720) THEN
        ITXT=66
        ISEQF=0
         CALL FILCON('USRTRN','data720.txt','OPEN','FORMATTED',
     +              'NEW',ITXT,ISEQF,IOST,IERR)

         IF (IERR.NE.0) THEN
         CALL FILERR('USRTRN','data720.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
        ENDIF
       ENDIF
        IF (KSTEP.EQ.740) THEN
        ITXT=67
        ISEQF=0
         CALL FILCON('USRTRN','data740.txt','OPEN','FORMATTED',
     +              'NEW',ITXT,ISEQF,IOST,IERR)

         IF (IERR.NE.0) THEN
         CALL FILERR('USRTRN','data740.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
        ENDIF
       ENDIF
        IF (KSTEP.EQ.760) THEN
        ITXT=68
        ISEQF=0
         CALL FILCON('USRTRN','data760.txt','OPEN','FORMATTED',
     +              'NEW',ITXT,ISEQF,IOST,IERR)

         IF (IERR.NE.0) THEN
         CALL FILERR('USRTRN','data760.txt','OPEN','NEW',
     +                ITXT,ISEQF,IOST,IERR)
        ENDIF
       ENDIF
C
C---- entrance1
        PI=3.14159265359
        IF ((KSTEP.EQ.40).OR.(KSTEP.GE.400)) THEN
        IF (MOD(KSTEP,20).EQ.0) THEN
            SUMMF=0.0
            SUMXP=0.0
            SUMU=0.0
             SUMW=0.0
           SUMWABS=0.0
          SUMRANG=0.0
          SUMAANG=0.0
C
        CALL IPREC('BLOCK-NUMBER-7','BLOCK','CENTRES',IPT,
     +             ILEN,JLEN,KLEN,CWORK,IWORK)
C
C       LOOP OVER PATCH
           I=14
```

```
            DO 198 J=1,JLEN
             DO 199 K=1,KLEN
              INODE=IP(I,J,K)
C
           WABS=W(INODE,1)+YP(INODE)*WNEW
           RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
           ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
                MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +           (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
                SUMMF=SUMMF   +MAF
                SUMXP=SUMXP   +MAF*XP(INODE)
                SUMU=SUMU    +MAF*U(INODE,1)
                 SUMW=SUMW    +MAF*W(INODE,1)
              SUMWABS=SUMWABS+MAF*WABS
             SUMRANG=SUMRANG+MAF*RELANG
             SUMAANG=SUMAANG+MAF*ABSANG
C
 199      CONTINUE
 198      CONTINUE
               PLNXM=    SUMXP/SUMMF
              UMEANM=     SUMU/SUMMF
              WMEANM=     SUMW/SUMMF
           WABSMEANM=  SUMWABS/SUMMF
               RANGM=  SUMRANG/SUMMF
               AANGM=  SUMAANG/SUMMF
                PLNRELM=ATAN2(WMEANM,UMEANM)*180/PI
                PLNABSM=ATAN2(WABSMEANM,UMEANM)*180/PI
C
          WRITE(ITXT,903)KSTEP,TIME,PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,
     +                AANGM,PLNRELM,PLNABSM
          WRITE(ITXT,*)'END OF ENTRANCE1 DATA'
 903     FORMAT(I4,9(2X,E17.10))
C
            ENDIF
          ENDIF
C
C---- entrance2
          IF ((KSTEP.EQ.40).OR.(KSTEP.GE.400)) THEN
           IF (MOD(KSTEP,20).EQ.0) THEN
C
                SUMMF=0.0
                SUMXP=0.0
                SUMU=0.0
                 SUMW=0.0
              SUMWABS=0.0
             SUMRANG=0.0
             SUMAANG=0.0
C
          CALL IPREC('BLOCK-NUMBER-1','BLOCK','CENTRES',IPT,
     +              ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
           DO 132 J=1,JLEN
           DO 133 I=1,7
           K=KLEN
            INODE=IP(I,J,K)
C
           WABS=W(INODE,1)+YP(INODE)*WNEW
           RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
           ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
                MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +           (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
                SUMMF=SUMMF   +MAF
                SUMXP=SUMXP   +MAF*XP(INODE)
                SUMU=SUMU    +MAF*U(INODE,1)
                 SUMW=SUMW    +MAF*W(INODE,1)
              SUMWABS=SUMWABS+MAF*WABS
             SUMRANG=SUMRANG+MAF*RELANG
             SUMAANG=SUMAANG+MAF*ABSANG
C
 133   CONTINUE
 132   CONTINUE
          CALL IPREC('BLOCK-NUMBER-6','BLOCK','CENTRES',IPT,
     +              ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
```

```
            DO 134 J=1,JLEN
             DO 135 I=10,ILEN
             K=KLEN
             INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
               SUMMF=SUMMF   +MAF
               SUMXP=SUMXP   +MAF*XP(INODE)
               SUMU=SUMU    +MAF*U(INODE,1)
                SUMW=SUMW    +MAF*W(INODE,1)
             SUMWABS=SUMWABS+MAF*WABS
            SUMRANG=SUMRANG+MAF*RELANG
            SUMAANG=SUMAANG+MAF*ABSANG
C
 135  CONTINUE
 134  CONTINUE
      CALL IPREC('BLOCK-NUMBER-8','BLOCK','CENTRES',IPT,
     +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
            I=7
            DO 136 J=1,JLEN
             DO 137 K=1,KLEN
             INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
               SUMMF=SUMMF   +MAF
               SUMXP=SUMXP   +MAF*XP(INODE)
               SUMU=SUMU    +MAF*U(INODE,1)
                SUMW=SUMW    +MAF*W(INODE,1)
             SUMWABS=SUMWABS+MAF*WABS
            SUMRANG=SUMRANG+MAF*RELANG
            SUMAANG=SUMAANG+MAF*ABSANG
C
 137  CONTINUE
 136  CONTINUE
               PLNXM=    SUMXP/SUMMF
              UMEANM=     SUMU/SUMMF
              WMEANM=     SUMW/SUMMF
           WABSMEANM=  SUMWABS/SUMMF
               RANGM=  SUMRANG/SUMMF
               AANGM=  SUMAANG/SUMMF
                PLNRELM=ATAN2(WMEANM,UMEANM)*180/PI
                PLNABSM=ATAN2(WABSMEANM,UMEANM)*180/PI

C
        WRITE(ITXT,903)KSTEP,TIME,PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,
     +               AANGM,PLNRELM,PLNABSM
        WRITE(ITXT,*)'END OF ENTRANCE2 DATA'
C
          ENDIF
        ENDIF
C
C---- entrance3
        IF ((KSTEP.EQ.40).OR.(KSTEP.GE.400)) THEN

        IF (MOD(KSTEP,20).EQ.0) THEN
C
               SUMMF=0.0
               SUMXP=0.0
               SUMU=0.0
                SUMW=0.0
             SUMWABS=0.0
            SUMRANG=0.0
            SUMAANG=0.0
C
      USRDOM(1)='BLOCK-NUMBER-1'
      USRDOM(2)='BLOCK-NUMBER-8'
```

```
      DO 100 DOMAINN=1,2
      CALL IPREC(USRDOM(DOMAINN),'BLOCK','CENTRES',IPT,
     +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C     LOOP OVER PATCH
          I=13
          DO 101 J=1,JLEN
           DO 102 K=1,KLEN
            INODE=IP(I,J,K)

C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
                SUMMF=SUMMF   +MAF
                SUMXP=SUMXP   +MAF*XP(INODE)
                SUMU=SUMU    +MAF*U(INODE,1)
                 SUMW=SUMW    +MAF*W(INODE,1)
              SUMWABS=SUMWABS+MAF*WABS
             SUMRANG=SUMRANG+MAF*RELANG
             SUMAANG=SUMAANG+MAF*ABSANG
C
 102      CONTINUE
 101      CONTINUE
 100      CONTINUE
      CALL IPREC('BLOCK-NUMBER-6','BLOCK','CENTRES',IPT,
     +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C     LOOP OVER PATCH
          I=4
          DO 103 J=1,JLEN
           DO 104 K=1,KLEN
            INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
               SUMMF=SUMMF   +MAF
               SUMXP=SUMXP   +MAF*XP(INODE)
               SUMU=SUMU    +MAF*U(INODE,1)
                SUMW=SUMW    +MAF*W(INODE,1)
             SUMWABS=SUMWABS+MAF*WABS
            SUMRANG=SUMRANG+MAF*RELANG
            SUMAANG=SUMAANG+MAF*ABSANG
C
 104      CONTINUE
 103      CONTINUE
           PLNXM=    SUMXP/SUMMF
          UMEANM=     SUMU/SUMMF
          WMEANM=     SUMW/SUMMF
        WABSMEANM=  SUMWABS/SUMMF
           RANGM=  SUMRANG/SUMMF
           AANGM=  SUMAANG/SUMMF
            PLNRELM=ATAN2(WMEANM,UMEANM)*180/PI
            PLNABSM=ATAN2(WABSMEANM,UMEANM)*180/PI
C
          WRITE(ITXT,903)KSTEP,TIME,PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,
     +                AANGM,PLNRELM,PLNABSM
          WRITE(ITXT,*)'END OF ENTRANCE3 DATA'
C
             ENDIF
          ENDIF
C
C---------middle1
          IF ((KSTEP.EQ.40).OR.(KSTEP.GE.400)) THEN
          IF (MOD(KSTEP,20).EQ.0) THEN
                SUMMF=0.0
                SUMXP=0.0
                SUMU=0.0
                 SUMW=0.0
              SUMWABS=0.0
             SUMRANG=0.0
```

```
            SUMAANG=0.0
C
       USRDOM(3)='BLOCK-NUMBER-2'
       USRDOM(4)='BLOCK-NUMBER-9'
       DO 105 DOMAINN=3,4
       CALL IPREC(USRDOM(DOMAINN),'BLOCK','CENTRES',IPT,
      +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
           I=2
           DO 106 J=1,JLEN
            DO 107 K=1,KLEN
             INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
      +         (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
               SUMMF=SUMMF   +MAF
               SUMXP=SUMXP   +MAF*XP(INODE)
               SUMU=SUMU    +MAF*U(INODE,1)
                SUMW=SUMW    +MAF*W(INODE,1)
             SUMWABS=SUMWABS+MAF*WABS
            SUMRANG=SUMRANG+MAF*RELANG
            SUMAANG=SUMAANG+MAF*ABSANG
C
 107      CONTINUE
 106      CONTINUE
 105      CONTINUE
       CALL IPREC('BLOCK-NUMBER-5','BLOCK','CENTRES',IPT,
      +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
           I=15
           DO 108 J=1,JLEN
            DO 109 K=1,KLEN
             INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
      +         (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
               SUMMF=SUMMF   +MAF
               SUMXP=SUMXP   +MAF*XP(INODE)
               SUMU=SUMU    +MAF*U(INODE,1)
                SUMW=SUMW    +MAF*W(INODE,1)
             SUMWABS=SUMWABS+MAF*WABS
            SUMRANG=SUMRANG+MAF*RELANG
            SUMAANG=SUMAANG+MAF*ABSANG
C
 109      CONTINUE
 108      CONTINUE
             PLNXM=    SUMXP/SUMMF
            UMEANM=     SUMU/SUMMF
            WMEANM=     SUMW/SUMMF
          WABSMEANM=  SUMWABS/SUMMF
             RANGM=  SUMRANG/SUMMF
             AANGM=  SUMAANG/SUMMF
                  PLNRELM=ATAN2(WMEANM,UMEANM)*180/PI
                  PLNABSM=ATAN2(WABSMEANM,UMEANM)*180/PI
C
          WRITE(ITXT,903)KSTEP,TIME,PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,
      +                  AANGM,PLNRELM,PLNABSM
          WRITE(ITXT,*)'END OF MID1 DATA'
C
             ENDIF
          ENDIF
C
C---------middle2
          IF ((KSTEP.EQ.40).OR.(KSTEP.GE.400)) THEN
          IF (MOD(KSTEP,20).EQ.0) THEN
                SUMMF=0.0
                SUMXP=0.0
                SUMU=0.0
```

```
                SUMW=0.0
               SUMWABS=0.0
              SUMRANG=0.0
              SUMAANG=0.0
C
       USRDOM(3)='BLOCK-NUMBER-2'
       USRDOM(4)='BLOCK-NUMBER-9'
       DO 139 DOMAINN=3,4
       CALL IPREC(USRDOM(DOMAINN),'BLOCK','CENTRES',IPT,
      +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
           I=5
           DO 140 J=1,JLEN
            DO 141 K=1,KLEN
             INODE=IP(I,J,K)
C
           WABS=W(INODE,1)+YP(INODE)*WNEW
           RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
           ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
                MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
      +         (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
                SUMMF=SUMMF   +MAF
                SUMXP=SUMXP   +MAF*XP(INODE)
                SUMU=SUMU    +MAF*U(INODE,1)
                 SUMW=SUMW    +MAF*W(INODE,1)
              SUMWABS=SUMWABS+MAF*WABS
             SUMRANG=SUMRANG+MAF*RELANG
             SUMAANG=SUMAANG+MAF*ABSANG
C
 141   CONTINUE
 140   CONTINUE
 139   CONTINUE
       CALL IPREC('BLOCK-NUMBER-5','BLOCK','CENTRES',IPT,
      +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
           I=12
           DO 142 J=1,JLEN
            DO 143 K=1,KLEN
             INODE=IP(I,J,K)
C
           WABS=W(INODE,1)+YP(INODE)*WNEW
           RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
           ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
                MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
      +         (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
                SUMMF=SUMMF   +MAF
                SUMXP=SUMXP   +MAF*XP(INODE)
                SUMU=SUMU    +MAF*U(INODE,1)
                 SUMW=SUMW    +MAF*W(INODE,1)
              SUMWABS=SUMWABS+MAF*WABS
             SUMRANG=SUMRANG+MAF*RELANG
             SUMAANG=SUMAANG+MAF*ABSANG
C
143    CONTINUE
142    CONTINUE
              PLNXM=    SUMXP/SUMMF
             UMEANM=     SUMU/SUMMF
             WMEANM=     SUMW/SUMMF
          WABSMEANM=  SUMWABS/SUMMF
              RANGM=  SUMRANG/SUMMF
              AANGM=  SUMAANG/SUMMF
               PLNRELM=ATAN2(WMEANM,UMEANM)*180/PI
               PLNABSM=ATAN2(WABSMEANM,UMEANM)*180/PI
C
       WRITE(ITXT,903)KSTEP,TIME,PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,
      +               AANGM,PLNRELM,PLNABSM
       WRITE(ITXT,*)'END OF MID2 DATA'
C
          ENDIF
       ENDIF
C
C---------middle3
       IF ((KSTEP.EQ.40).OR.(KSTEP.GE.400)) THEN
       IF (MOD(KSTEP,20).EQ.0) THEN
```

```
                SUMMF=0.0
                SUMXP=0.0
                SUMU=0.0
                 SUMW=0.0
               SUMWABS=0.0
              SUMRANG=0.0
              SUMAANG=0.0
C
       USRDOM(3)='BLOCK-NUMBER-2'
       USRDOM(4)='BLOCK-NUMBER-9'
       DO 110 DOMAINN=3,4
       CALL IPREC(USRDOM(DOMAINN),'BLOCK','CENTRES',IPT,
      +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
            I=8
            DO 111 J=1,JLEN
             DO 112 K=1,KLEN
              INODE=IP(I,J,K)
C
           WABS=W(INODE,1)+YP(INODE)*WNEW
           RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
           ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
                MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
                SUMMF=SUMMF   +MAF
                SUMXP=SUMXP   +MAF*XP(INODE)
                SUMU=SUMU    +MAF*U(INODE,1)
                 SUMW=SUMW    +MAF*W(INODE,1)
              SUMWABS=SUMWABS+MAF*WABS
             SUMRANG=SUMRANG+MAF*RELANG
             SUMAANG=SUMAANG+MAF*ABSANG
C
 112       CONTINUE
 111       CONTINUE
 110       CONTINUE
       CALL IPREC('BLOCK-NUMBER-5','BLOCK','CENTRES',IPT,
      +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
            I=9
            DO 113 J=1,JLEN
             DO 114 K=1,KLEN
              INODE=IP(I,J,K)
C
           WABS=W(INODE,1)+YP(INODE)*WNEW
           RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
           ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
                MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
                SUMMF=SUMMF   +MAF
                SUMXP=SUMXP   +MAF*XP(INODE)
                SUMU=SUMU    +MAF*U(INODE,1)
                 SUMW=SUMW    +MAF*W(INODE,1)
              SUMWABS=SUMWABS+MAF*WABS
             SUMRANG=SUMRANG+MAF*RELANG
             SUMAANG=SUMAANG+MAF*ABSANG
C
 114       CONTINUE
 113       CONTINUE
              PLNXM=    SUMXP/SUMMF
             UMEANM=     SUMU/SUMMF
             WMEANM=     SUMW/SUMMF
           WABSMEANM=  SUMWABS/SUMMF
               RANGM=  SUMRANG/SUMMF
               AANGM=  SUMAANG/SUMMF
                PLNRELM=ATAN2(WMEANM,UMEANM)*180/PI
                PLNABSM=ATAN2(WABSMEANM,UMEANM)*180/PI
C
       WRITE(ITXT,903)KSTEP,TIME,PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,
      +               AANGM,PLNRELM,PLNABSM
       WRITE(ITXT,*)'END OF MID3 DATA'
C
          ENDIF
       ENDIF
C
```

```
C---------middle4
       IF ((KSTEP.EQ.40).OR.(KSTEP.GE.400)) THEN
       IF (MOD(KSTEP,20).EQ.0) THEN
             SUMMF=0.0
             SUMXP=0.0
             SUMU=0.0
              SUMW=0.0
            SUMWABS=0.0
           SUMRANG=0.0
           SUMAANG=0.0
C
      USRDOM(3)='BLOCK-NUMBER-2'
      USRDOM(4)='BLOCK-NUMBER-9'
      DO 180 DOMAINN=3,4

      CALL IPREC(USRDOM(DOMAINN),'BLOCK','CENTRES',IPT,
     +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C     LOOP OVER PATCH
          I=11
          DO 181 J=1,JLEN
           DO 182 K=1,KLEN
            INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
               SUMMF=SUMMF   +MAF
               SUMXP=SUMXP   +MAF*XP(INODE)
               SUMU=SUMU    +MAF*U(INODE,1)
                SUMW=SUMW    +MAF*W(INODE,1)
             SUMWABS=SUMWABS+MAF*WABS
            SUMRANG=SUMRANG+MAF*RELANG
            SUMAANG=SUMAANG+MAF*ABSANG
C
 182      CONTINUE
 181      CONTINUE
 180      CONTINUE
       CALL IPREC('BLOCK-NUMBER-5','BLOCK','CENTRES',IPT,
      +           ILEN,JLEN,KLEN,CWORK,IWORK)
C
C     LOOP OVER PATCH
          I=6
          DO 183 J=1,JLEN
           DO 184 K=1,KLEN
            INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
               SUMMF=SUMMF   +MAF
               SUMXP=SUMXP   +MAF*XP(INODE)
               SUMU=SUMU    +MAF*U(INODE,1)
                SUMW=SUMW    +MAF*W(INODE,1)
             SUMWABS=SUMWABS+MAF*WABS
            SUMRANG=SUMRANG+MAF*RELANG
            SUMAANG=SUMAANG+MAF*ABSANG
C
 184      CONTINUE
 183      CONTINUE
              PLNXM=    SUMXP/SUMMF
            UMEANM=     SUMU/SUMMF
            WMEANM=     SUMW/SUMMF
          WABSMEANM=  SUMWABS/SUMMF
              RANGM=  SUMRANG/SUMMF
              AANGM=  SUMAANG/SUMMF
               PLNRELM=ATAN2(WMEANM,UMEANM)*180/PI
               PLNABSM=ATAN2(WABSMEANM,UMEANM)*180/PI
C
        WRITE(ITXT,903)KSTEP,TIME,PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,
     +                 AANGM,PLNRELM,PLNABSM
        WRITE(ITXT,*)'END OF MID4 DATA'
```

```
C
          ENDIF
        ENDIF
C
C---------middle5
        IF ((KSTEP.EQ.40).OR.(KSTEP.GE.400)) THEN
        IF (MOD(KSTEP,20).EQ.0) THEN
              SUMMF=0.0
              SUMXP=0.0
              SUMU=0.0
               SUMW=0.0
             SUMWABS=0.0
            SUMRANG=0.0
            SUMAANG=0.0
C
       USRDOM(3)='BLOCK-NUMBER-2'
        USRDOM(4)='BLOCK-NUMBER-9'
        DO 115 DOMAINN=3,4
        CALL IPREC(USRDOM(DOMAINN),'BLOCK','CENTRES',IPT,
      +            ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
           I=15
           DO 116 J=1,JLEN
            DO 117 K=1,KLEN
             INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
      +         (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
              SUMMF=SUMMF   +MAF
              SUMXP=SUMXP   +MAF*XP(INODE)
              SUMU=SUMU    +MAF*U(INODE,1)
               SUMW=SUMW    +MAF*W(INODE,1)
            SUMWABS=SUMWABS+MAF*WABS
           SUMRANG=SUMRANG+MAF*RELANG
             SUMAANG=SUMAANG+MAF*ABSANG
C
 117      CONTINUE
 116      CONTINUE
 115      CONTINUE
        CALL IPREC('BLOCK-NUMBER-5','BLOCK','CENTRES',IPT,
      +            ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
           I=2
           DO 118 J=1,JLEN
            DO 119 K=1,KLEN
             INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
      +         (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
              SUMMF=SUMMF   +MAF
              SUMXP=SUMXP   +MAF*XP(INODE)
              SUMU=SUMU    +MAF*U(INODE,1)
               SUMW=SUMW    +MAF*W(INODE,1)
            SUMWABS=SUMWABS+MAF*WABS
           SUMRANG=SUMRANG+MAF*RELANG
           SUMAANG=SUMAANG+MAF*ABSANG
C
 119      CONTINUE
 118      CONTINUE
            PLNXM=    SUMXP/SUMMF
           UMEANM=     SUMU/SUMMF
           WMEANM=     SUMW/SUMMF
         WABSMEANM=  SUMWABS/SUMMF
            RANGM=  SUMRANG/SUMMF
            AANGM=  SUMAANG/SUMMF
             PLNRELM=ATAN2(WMEANM,UMEANM)*180/PI
             PLNABSM=ATAN2(WABSMEANM,UMEANM)*180/PI
C
```

```
        WRITE(ITXT,903)KSTEP,TIME,PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,
     +               AANGM,PLNRELM,PLNABSM
        WRITE(ITXT,*)'END OF MID5 DATA'
C
           ENDIF
        ENDIF
C
C---------exit1
        IF ((KSTEP.EQ.40).OR.(KSTEP.GE.400)) THEN
        IF (MOD(KSTEP,20).EQ.0) THEN
              SUMMF=0.0
              SUMXP=0.0
              SUMU=0.0
               SUMW=0.0
             SUMWABS=0.0
            SUMRANG=0.0
            SUMAANG=0.0
C
       USRDOM(5)='BLOCK-NUMBER-3'
       USRDOM(6)='BLOCK-NUMBER-10'
C
       DO 120 DOMAINN=5,6
       CALL IPREC(USRDOM(DOMAINN),'BLOCK','CENTRES',IPT,
     +            ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
           I=4
           DO 121 J=1,JLEN
            DO 122 K=1,KLEN
             INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
               SUMMF=SUMMF   +MAF
               SUMXP=SUMXP   +MAF*XP(INODE)
               SUMU=SUMU    +MAF*U(INODE,1)
                SUMW=SUMW    +MAF*W(INODE,1)
             SUMWABS=SUMWABS+MAF*WABS
            SUMRANG=SUMRANG+MAF*RELANG
            SUMAANG=SUMAANG+MAF*ABSANG
C
 122      CONTINUE

 121      CONTINUE
 120      CONTINUE
       CALL IPREC('BLOCK-NUMBER-4','BLOCK','CENTRES',IPT,
     +            ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
           I=13
           DO 123 J=1,JLEN
            DO 124 K=1,KLEN
             INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
               SUMMF=SUMMF   +MAF
               SUMXP=SUMXP   +MAF*XP(INODE)
               SUMU=SUMU    +MAF*U(INODE,1)
                SUMW=SUMW    +MAF*W(INODE,1)
             SUMWABS=SUMWABS+MAF*WABS
            SUMRANG=SUMRANG+MAF*RELANG
            SUMAANG=SUMAANG+MAF*ABSANG
C
 124      CONTINUE
 123      CONTINUE
             PLNXM=    SUMXP/SUMMF
            UMEANM=     SUMU/SUMMF
            WMEANM=     SUMW/SUMMF
          WABSMEANM=  SUMWABS/SUMMF
```

```
                RANGM=  SUMRANG/SUMMF
                AANGM=  SUMAANG/SUMMF
                 PLNRELM=ATAN2(WMEANM,UMEANM)*180/PI
                 PLNABSM=ATAN2(WABSMEANM,UMEANM)*180/PI
C
        WRITE(ITXT,903)KSTEP,TIME,PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,
     +                 AANGM,PLNRELM,PLNABSM
        WRITE(ITXT,*)'END OF EXIT1 DATA'
C
           ENDIF
        ENDIF
C
C---- exit2
        IF ((KSTEP.EQ.40).OR.(KSTEP.GE.400)) THEN
        IF (MOD(KSTEP,20).EQ.0) THEN
C
                SUMMF=0.0
                SUMXP=0.0
                SUMU=0.0
                 SUMW=0.0
               SUMWABS=0.0
              SUMRANG=0.0

              SUMAANG=0.0
C
       CALL IPREC('BLOCK-NUMBER-3','BLOCK','CENTRES',IPT,
     +            ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
            K=13
        DO 170 J=1,JLEN
         DO 171 I=12,ILEN
             INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
              SUMMF=SUMMF   +MAF
              SUMXP=SUMXP   +MAF*XP(INODE)
              SUMU=SUMU    +MAF*U(INODE,1)
               SUMW=SUMW    +MAF*W(INODE,1)
            SUMWABS=SUMWABS+MAF*WABS
           SUMRANG=SUMRANG+MAF*RELANG
           SUMAANG=SUMAANG+MAF*ABSANG
C
 171   CONTINUE
 170   CONTINUE
       CALL IPREC('BLOCK-NUMBER-4','BLOCK','CENTRES',IPT,
     +            ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
            K=13
            DO 172 J=1,JLEN
             DO 173 I=1,7
             INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
              SUMMF=SUMMF   +MAF
              SUMXP=SUMXP   +MAF*XP(INODE)
              SUMU=SUMU    +MAF*U(INODE,1)
               SUMW=SUMW    +MAF*W(INODE,1)
            SUMWABS=SUMWABS+MAF*WABS
           SUMRANG=SUMRANG+MAF*RELANG
           SUMAANG=SUMAANG+MAF*ABSANG
C
 173   CONTINUE
 172   CONTINUE
       CALL IPREC('BLOCK-NUMBER-10','BLOCK','CENTRES',IPT,
     +            ILEN,JLEN,KLEN,CWORK,IWORK)
C
```

```
C      LOOP OVER PATCH
            I=8
            DO 174 J=1,JLEN
             DO 175 K=1,KLEN
             INODE=IP(I,J,K)
C
           WABS=W(INODE,1)+YP(INODE)*WNEW
           RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
           ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
                MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +           (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
                SUMMF=SUMMF   +MAF
                SUMXP=SUMXP   +MAF*XP(INODE)
                SUMU=SUMU    +MAF*U(INODE,1)
                 SUMW=SUMW    +MAF*W(INODE,1)
              SUMWABS=SUMWABS+MAF*WABS
             SUMRANG=SUMRANG+MAF*RELANG
             SUMAANG=SUMAANG+MAF*ABSANG
C
 175   CONTINUE
 174   CONTINUE
                PLNXM=    SUMXP/SUMMF
              UMEANM=     SUMU/SUMMF
              WMEANM=     SUMW/SUMMF
            WABSMEANM=  SUMWABS/SUMMF
                RANGM=  SUMRANG/SUMMF

                AANGM=  SUMAANG/SUMMF
                 PLNRELM=ATAN2(WMEANM,UMEANM)*180/PI
                 PLNABSM=ATAN2(WABSMEANM,UMEANM)*180/PI
C
          WRITE(ITXT,903)KSTEP,TIME,PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,
     +                AANGM,PLNRELM,PLNABSM
          WRITE(ITXT,*)'END OF EXIT2 DATA'
C
             ENDIF
          ENDIF
C
C----------exit3
          IF ((KSTEP.EQ.40).OR.(KSTEP.GE.400)) THEN
          IF (MOD(KSTEP,20).EQ.0) THEN
                SUMMF=0.0
                SUMXP=0.0
                SUMU=0.0
                 SUMW=0.0
              SUMWABS=0.0
             SUMRANG=0.0
             SUMAANG=0.0
C
       CALL IPREC('BLOCK-NUMBER-3','BLOCK','CENTRES',IPT,
     +            ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
            DO 176 J=1,JLEN
            DO 177 I=14,ILEN
            K=KLEN
             INODE=IP(I,J,K)
C
           WABS=W(INODE,1)+YP(INODE)*WNEW
           RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
           ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
                MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +           (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
                SUMMF=SUMMF   +MAF
                SUMXP=SUMXP   +MAF*XP(INODE)
                SUMU=SUMU    +MAF*U(INODE,1)
                 SUMW=SUMW    +MAF*W(INODE,1)
              SUMWABS=SUMWABS+MAF*WABS
             SUMRANG=SUMRANG+MAF*RELANG
             SUMAANG=SUMAANG+MAF*ABSANG
C
 177   CONTINUE
 176   CONTINUE
       CALL IPREC('BLOCK-NUMBER-4','BLOCK','CENTRES',IPT,
     +            ILEN,JLEN,KLEN,CWORK,IWORK)
C
```

```
C      LOOP OVER PATCH
            K=KLEN
            DO 178 J=1,JLEN
             DO 179 I=1,3
             INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
               SUMMF=SUMMF   +MAF
               SUMXP=SUMXP   +MAF*XP(INODE)
               SUMU=SUMU    +MAF*U(INODE,1)
                SUMW=SUMW    +MAF*W(INODE,1)
             SUMWABS=SUMWABS+MAF*WABS
             SUMRANG=SUMRANG+MAF*RELANG
             SUMAANG=SUMAANG+MAF*ABSANG
C
 179   CONTINUE
 178   CONTINUE
       CALL IPREC('BLOCK-NUMBER-10','BLOCK','CENTRES',IPT,
     +            ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
            I=13
            DO 190 J=1,JLEN
             DO 191 K=1,KLEN
             INODE=IP(I,J,K)
C
          WABS=W(INODE,1)+YP(INODE)*WNEW
          RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
          ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
               MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +          (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
               SUMMF=SUMMF   +MAF
               SUMXP=SUMXP   +MAF*XP(INODE)
               SUMU=SUMU    +MAF*U(INODE,1)
                SUMW=SUMW    +MAF*W(INODE,1)
             SUMWABS=SUMWABS+MAF*WABS
             SUMRANG=SUMRANG+MAF*RELANG
             SUMAANG=SUMAANG+MAF*ABSANG
C
 191   CONTINUE
 190   CONTINUE
                PLNXM=    SUMXP/SUMMF
              UMEANM=     SUMU/SUMMF
              WMEANM=     SUMW/SUMMF
            WABSMEANM=  SUMWABS/SUMMF
                RANGM=  SUMRANG/SUMMF
                AANGM=  SUMAANG/SUMMF
                 PLNRELM=ATAN2(WMEANM,UMEANM)*180/PI
                 PLNABSM=ATAN2(WABSMEANM,UMEANM)*180/PI
C
        WRITE(ITXT,903)KSTEP,TIME,PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,
     +                 AANGM,PLNRELM,PLNABSM
        WRITE(ITXT,*)'END OF EXIT3 DATA'
C
           ENDIF
        ENDIF
C
C---------exit4
        IF ((KSTEP.EQ.40).OR.(KSTEP.GE.400)) THEN
        IF (MOD(KSTEP,20).EQ.0) THEN
               SUMMF=0.0
               SUMXP=0.0
               SUMU=0.0
                SUMW=0.0
             SUMWABS=0.0
            SUMRANG=0.0
            SUMAANG=0.0
C
       CALL IPREC('BLOCK-NUMBER-11','BLOCK','CENTRES',IPT,
     +            ILEN,JLEN,KLEN,CWORK,IWORK)
C
C      LOOP OVER PATCH
```

```
            I=2
            DO 130 J=1,JLEN

             DO 131 K=1,KLEN
              INODE=IP(I,J,K)
C
           WABS=W(INODE,1)+YP(INODE)*WNEW
           RELANG=ATAN2(W(INODE,1),U(INODE,1))*180/PI
           ABSANG=ATAN2(WABS,U(INODE,1))*180/PI
                MAF=DEN(INODE,1)*((U(INODE,1)*AREA(INODE,1))+
     +           (V(INODE,1)*AREA(INODE,2))+(W(INODE,1)*AREA(INODE,3)))
                SUMMF=SUMMF   +MAF
                SUMXP=SUMXP   +MAF*XP(INODE)
                SUMU=SUMU    +MAF*U(INODE,1)
                 SUMW=SUMW    +MAF*W(INODE,1)
              SUMWABS=SUMWABS+MAF*WABS
                SUMRANG=SUMRANG+MAF*RELANG
                SUMAANG=SUMAANG+MAF*ABSANG
C
 131       CONTINUE
 130       CONTINUE
               PLNXM=    SUMXP/SUMMF
              UMEANM=     SUMU/SUMMF
              WMEANM=     SUMW/SUMMF
           WABSMEANM=  SUMWABS/SUMMF
               RANGM=  SUMRANG/SUMMF
               AANGM=  SUMAANG/SUMMF
                PLNRELM=ATAN2(WMEANM,UMEANM)*180/PI
                PLNABSM=ATAN2(WABSMEANM,UMEANM)*180/PI
C
          WRITE(ITXT,903)KSTEP,TIME,PLNXM,UMEANM,WMEANM,WABSMEANM,RANGM,
       +                 AANGM,PLNRELM,PLNABSM
          WRITE(ITXT,*)'END OF EXIT4 DATA'
C
             ENDIF
          ENDIF
C
C+++++++++++++++ END OF USER AREA 5 +++++++++++++++++++++++++++++
C
          RETURN
          END
```

THE DYNAMIC RESPONSE OF TURBINE FLOWMETERS IN LIQUID FLOWS

B. LEE R. CHEESEWRIGHT C. CLARK

Systems Engineering Department, Brunel University, Uxbridge, Middlesex, UK

ABSTRACT

The dynamic response of turbine flowmeters in low pressure gas flows (i.e. where the rotational inertia of the fluid is negligible) is well understood and methods for correcting meter signals for a lack of response are available. For liquid flows there has been a limited amount of experimental work on the response of meters to step changes but no reports have been found of the response of meters to sinusoidally pulsating flows.

A range of different sizes of meter from ¼ inch up to 1 inch have been subjected to sinusoidally pulsating flows at pulsation frequencies up to 300 Hz. Results are presented which show that although the mean flow rates indicated by the meters do not show the large levels of 'over-registration' associated with gas flows, there is significant attenuation of the amplitudes of pulsations. An attempt is made to show the dependence of the attenuation on the flow pulsation amplitude and the pulsation frequency. The attenuation is also compared to the predictions of an Atkinson type of model of the response, using values of the meter response parameter scaled to the appropriate fluid density.

Key words: turbine meters, dynamic response, liquid flow

INTRODUCTION

Turbine flowmeters have been used extensively in fluid measurement and the ability of this flowmeter to respond rapidly to transient flow conditions is an important characteristic. In sinusoidally pulsating flows, the meter accuracy deteriorates with increases in the amplitude and with increases in the frequency of pulsation. If the meter does not rapidly follow the flow rate, then erroneous mean flow measurements as well as erroneous time varying flow measurements can occur.

Within a pulsation cycle, the increasing flow creates higher incidence angles on the turbine blades giving the rotor relatively rapid acceleration; when the flow decreases the incidence angles on the blades are lower and the rotor may stall with low lift and hence experience low deceleration [1]. A combination of these effects causes two common, known problems in turbine flowmetering. Firstly there is a difference between the pulsation amplitude indicated by the meter and the true pulsation amplitude; secondly the mean blade passing frequency is higher than that which would occur with the corresponding steady flow. These two effects are commonly termed "amplitude attenuation" and "over-registration" respectively.

The occurrence of these errors has been known for nearly 70 years, and a number of workers [2, 3, 4] have published suggestions of possible procedures for the estimation of correction factors for meters operating in gas flows. However, in pulsating liquid flows, there is a lack of experimental data on the meter dynamic response. Therefore it is of interest to investigate, both theoretically and experimentally, the dynamic response of small turbine flowmeters under pulsating liquid flows, so that the undesirable effects of pulsation on accuracy of flow measurement can be understood and appropriate action can be taken to avoid, or correct for, metering errors.

The published theories of transient meter response in gas flow are all very similar [5, 6, 7] and these treatments assume, either implicitly or explicitly, that the rotational inertia of the fluid contained within the turbine rotor is negligible compared to that of the rotor itself. In some cases [8, 9], there are no friction effects; and the flow is assumed to follow the blades. This approach can be generalised in the form of the equation shown below.

$$b \frac{d\dot{V}_m}{dt} = \dot{V}_a^2 - \dot{V}_m \dot{V}_a \qquad (1)$$

where $\dot{V}_m$ is the volume flow rate indicated by the meter (= $k f_b$, where k is a meter constant and f_b is the blade passing frequency); $\dot{V}_a$ is the true volume flow rate and t is time. The response

parameter, b, determines how quickly the meter responds to changes in the flow rate; it depends on: the inertia of the rotor I_R , the hydrodynamic properties of the fluid and the aerodynamic characteristics of the blades. A simple representation of b is given by

$$b = \frac{I_R}{\rho r^2} \qquad (2)$$

where r is mean radius of rotor and ρ is fluid density.

Atkinson [10] developed a software tool to calculate the over-registration error of a turbine meter in a pulsating gas flow. The tool is based on a normalised form of equation (1), assuming sinusoidal pulsations.

The only published attempt at a general representation of the response of a turbine meter in a liquid (or high density gas) flow is that by Dijstelbergen [11]. His equation effectively redefines the parameter b as :

$$b' = \frac{(I_R + I_f)}{\rho r^2} \qquad (3)$$

where I_f is the rotational inertia of the fluid contained within the envelope of the turbine rotor. However, he also includes a term involving the product of I_f and the time rate of change of the true flow through the meter. The significance of this second term is not clear and the inclusion of it in any attempt to correct for over-registration and/or attenuation errors presents problems because the rate of change of the true flow is not a known quantity; also because it implies that b and I_f need to be known separately. Cheesewright and Clark [12] have reported that an attempt to correlate the results of (small) step response tests using the Dijstelbergen equation was not very satisfactory.

Other published reports of work on the response of turbine meters to liquid flows include the experimental work of Higson [13], and the theoretical work of Jepson [14]. However these both deal with the response to a flow which starts (instantaneously) from zero and it is doubtful whether the exact mechanism of the response to such a change will be the same as that for either small step changes or sinusoidal flow pulsations. The step response tests reported by Cheesewright and Clark [12] did not included start-up from zero but they did include steps to zero and in that case it was demonstrated that the whole mechanism of the response was different because the forces on the turbine rotor are dominated by disk friction effects rather than by fluid dynamic forces on the blades.

In experiments which are described below, the details of the responses of a number of small turbine flowmeters to (sinusoidally) pulsating flow have been measured. The initial attempt to correlate these measurements, which is reported in the present paper, involved an approach similar to that used by Atkinson for gas flows, but with the meter response parameter modified to include the rotational inertia of the fluid contained within the turbine rotor, as outlined above.

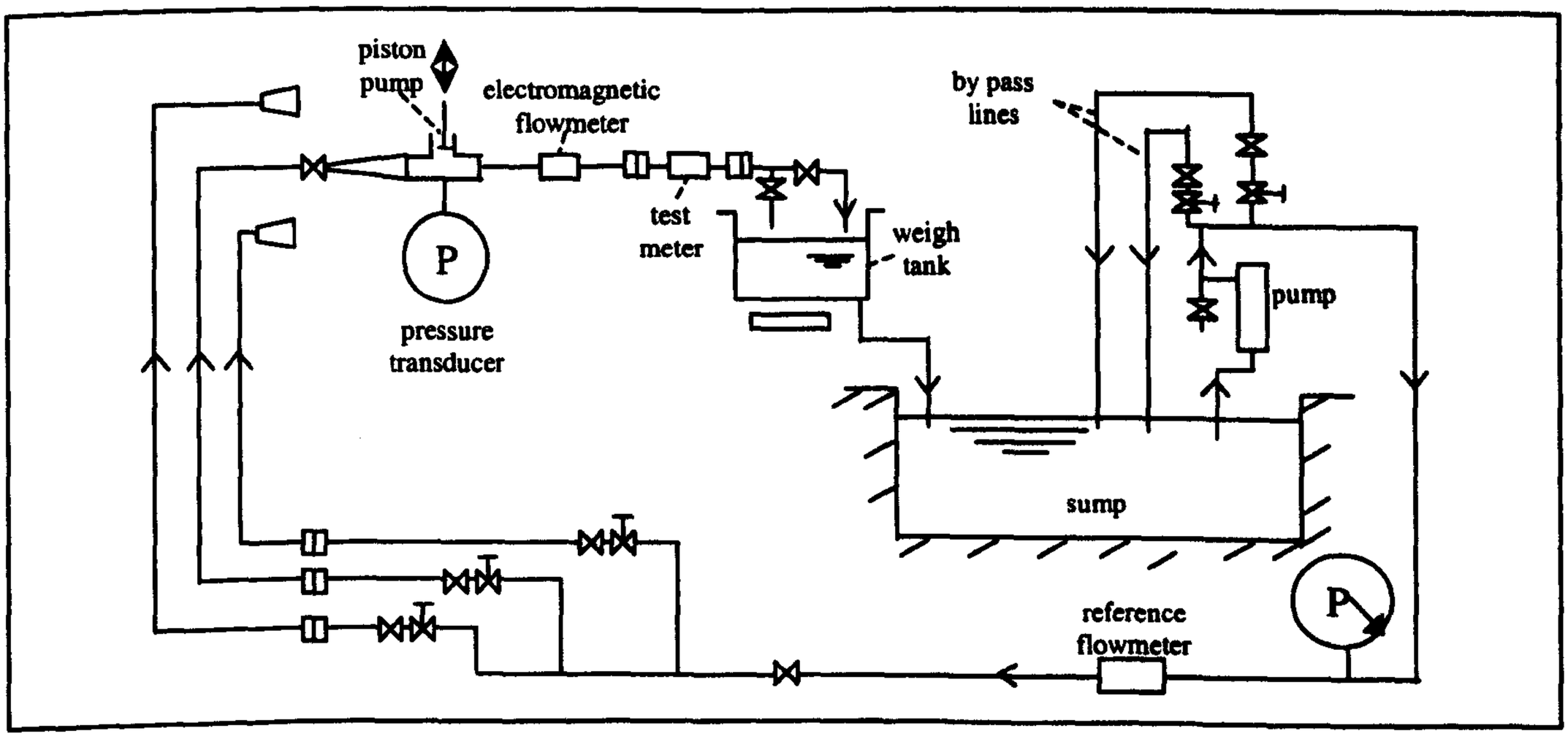


Figure 1 A schematic diagram of the test rig

FLOW TEST FACILITY AND TEST PROCEDURE

A schematic diagram of the flow test rig, designed to allow testing of meters in the size range ¼ in. to 1 in., is shown in Figure 1. Steady flow was produced by a positive displacement pump with a helical rotor (Monopump model CE064MS1R3/H421) driven at a fixed speed. The pump intake was fed from a sump holding in excess of 30 m^3 of water. The required flow rate through the test meter was attained by adjusting the fraction of pump outflow diverted through two bypass lines. This provided the nominal meter flow rates, required for the present tests, of 0.095 kg/s to 1.75 kg/s. Continuously timed gravimetric collection using a weigh tank provided a primary flow rate standard with a measurement uncertainty of ±0.1%. An electromagnetic flowmeter provided a secondary flow rate reference. The positive displacement pump produced a steady flow condition except for very small fluctuations at approximately 11.5 Hz and 23 Hz due to the two driving rotors each with two lobes. However, the magnitude of these pulsations was very small compared with the sinusoidal pulsations produced by the purpose built piston pump.

The piston pump was driven by an electromagnetic actuator, over a frequency range of 5 Hz to 300 Hz. The amplitude of the pulsations was varied within the limit imposed by the maximum actuator force of 600 N and the need to avoid cavitation. The piston pump was connected to the main flow line through a T-piece, a short distance upstream of a second electromagnetic flowmeter. In order to ensure that a very high fraction of the flow pulsation was added to the downstream flow (through the test meter), the mean flow component was supplied at an upstream pressure of 20 bar. An appropriate length of a relatively small-bore tube dropped the pressure to 2 bar at the location of the piston pump. Pulsation amplitudes were restricted to ensure that the minimum pressure within the pulsation cycle remained above atmospheric pressure.

The pulsation flow waveform was obtained from a commercially available electromagnetic (EM) flowmeter, 1" Krohne (model IFM4010K/D/6), located between the pulsator and the turbine flowmeter. The EM meter was energised (unconventionally) from a 12V d.c. source. In order to avoid effects of shifting d.c. levels (due to electrolytic action at the meter electrodes), the meter signal was a.c. coupled to a high gain (10 000 to 150 000) amplifier to produce signal amplitudes suitable for data logging.

This procedure allowed pulsations to be recorded over a frequency range of 5 Hz to 300 Hz and thus avoided the frequency limitation that would have arisen from the conventional a.c. excitation of the meter. The EM signal was calibrated with the aid of the signal from an accelerometer, which sensed the motion of the pulsator piston rod. The accelerometer signal was integrated to give the velocity of the piston motion; the instantaneous volume flow rate during the pulsation cycle could be found by multiplying the velocity by the cross sectional area of the piston. The repeatability of this calibration was better than 5% over a period of three days.

The turbine meter under test was placed downstream of the electromagnetic flowmeter and the outlet from the meter was fed to a weigh tank. An electromagnetic pick-up on the meter generates a signal each time a turbine blade passes and this signal was amplified and digitised. The resulting digital time history of the meter signal was analysed using the LABVIEW (V. 5.1) graphical programming language. Not all of the test meters produced a signal from the electro-magnetic pick-up which was absolutely sinusoidal. Figure 2a shows an example of the digitised meter output signal for a pulsation flow test, from which it can be seen that the signal has the features of a sawtooth waveform.

The conventional method of processing turbine meter signals is to convert the quasi sinusoidal signal to a pulse signal with a pulse generated at either the + to – zero crossing or the – to + zero crossing. The reciprocal of the time between successive pulses is then the blade passing frequency. However, in the present work it was desired to test meters at the highest possible flow pulsation frequencies, and since one of the features of interest was the pulsation amplitude attenuation, this required some 8 to 10 data points per pulsation wave which would have restricted the pulsation frequency to $1/8^{th}$ of the blade passing frequency. It is clearly possible to generate pulses at both of the zero crossings in a given cycle of the signal from the pick-up but consideration of the waveform displayed in Figure 2a shows that the intervals between such pulses cannot be used to give two independent estimates of the blade passing frequency per signal cycle. The best that it is possible to do is to take the period between two successive + to – zero crossings and to associate that with the **average** blade passing frequency over that period and then to take the period between the two – to + zero crossings and to associate that with the average over that period. Thus it is possible to get twice as many data points per signal cycle, **but** successive data points are averages over (partially)

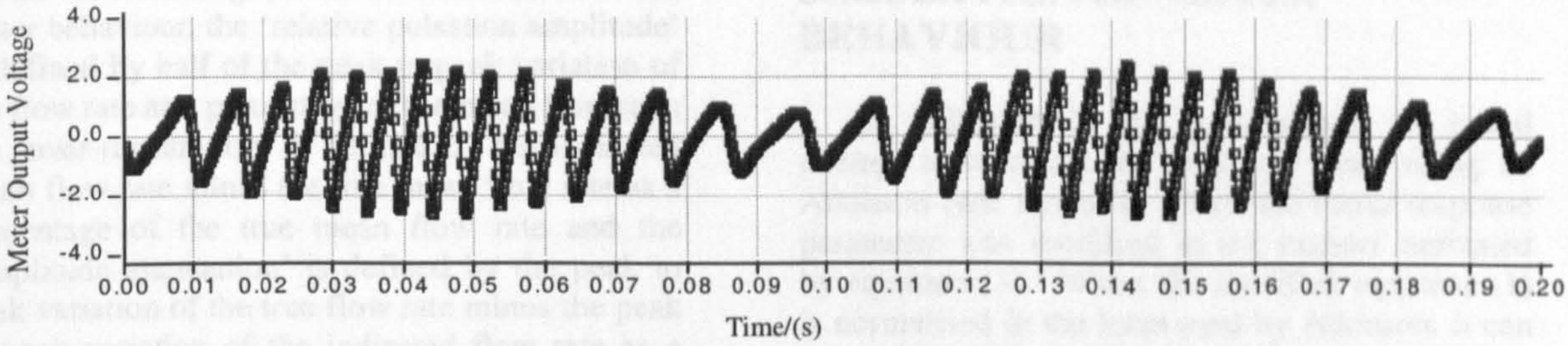


Figure 2a Turbine meter output signal reconstructed from digital data

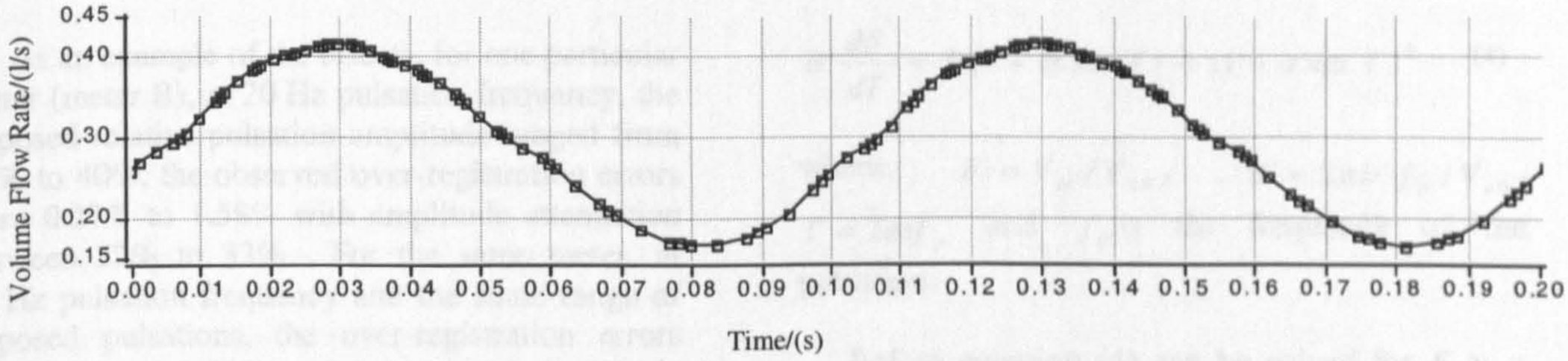


Figure 2b Turbine flow waveform processed by using four points per cycle technique for waveform in Figure 2a

overlapping periods. It is even possible to extend this process by identifying successive maxima and successive minima, thus giving 4 data points per signal cycle but each of the data points will be an average over a period of one signal cycle, with a 75% overlap between successive periods.

Figure 2b shows an example of a pulsation waveform constructed from 4 data points per signal cycle and with this approach it is potentially possible to examine the meter response to flow pulsations at frequencies as high as 1/3rd of the blade passing frequency. However, it must be noted that the identification of maxima and minima will be inherently less accurate than the identification of zero crossings. For some tests it was found that the data points thus generated were too inaccurate to be of value so that it was necessary to revert to only 2 data points per signal cycle. It must be noted, from Figure 2b, that the data points are not equally spaced in time; there is a greater concentration of data points during times of high flow rate than during times of low flow rate. Thus a simple average of all the estimates of the flow rate does not give a true mean flow rate; it is necessary, either to integrate the flow rate/time history or, as was done in the present work, to digitally re-sample the flow rate/time history at equal intervals of time.

Five meters were tested and their characteristics and testing conditions are given in Table 1. The meters were tested with pulsation frequencies ranging from 5 Hz up to a maximum frequency which varied from meter to meter and which was dictated by the blade passing frequency produced by the mean flow rate. Three different pulsation amplitudes were applied at each frequency.

Meter	Blade No.	Experimental K factor /(pulse/litre)	Operating flowrate /(litre/s)	Maximum pulsation frequency /(Hz)
A	3	1608	0.096	20
B	3	517	0.290	120
C	5	9017	0.096	80
D	6	2614	0.290	300
E	5	187	1.700	120

Table 1 Brief characteristics and test conditions of each meter

RESULTS

The results for each meter were qualitatively very similar. At the largest pulsation amplitudes they all experienced significant over-registration for pulsation frequencies above 20 Hz and significant pulsation amplitude attenuation, for pulsation frequencies above 5 Hz. The maximum over-registration observed was 5%. The tests showed that both the over-registration error and the amplitude attenuation increased significantly with increasing pulsation frequency but they only increased slowly with increasing pulsation amplitude.

In the following quantitative discussion of the meter behaviour, the 'relative pulsation amplitude' is defined by half of the peak to peak variation of the flow rate as a percentage of the mean flow rate; the 'over-registration' is defined by the indicated mean flow rate minus the true mean flow rate as a percentage of the true mean flow rate and the 'amplitude attenuation' is defined by the peak to peak variation of the true flow rate minus the peak to peak variation of the indicated flow rate as a percentage of the peak to peak variation of the true flow rate.

As an example of the effects, for one particular meter (meter B), at 20 Hz pulsation frequency, the imposed relative pulsation amplitude ranged from 17% to 40%, the observed over-registration errors were 0.27% to 1.58% with amplitude attenuation between 32% to 33%. For the same meter, at 40 Hz pulsation frequency and the same range of imposed pulsations, the over-registration errors were between 0.53% and 3.40% with amplitude attenuation between 43% and 44%. Figure 3 shows the true flow waveform as compared to the meter indicated flow waveform when 40% relative pulsation amplitude is applied at 20 Hz. The waveform of the true flow was obtained from the EM flowmeter and this was off-set to give a mean flow rate which agreed with that obtained from the weigh tank. Individual data points are not shown in Figure 3 (and 4) because they would overlap one another.

In assessing the significance of the above values of the over-registration error, it must be noted that the uncertainties quoted by the manufacturers for the meters used in these tests ranged from ±0.5% of full scale to ±1.0% of full scale (over the linear range of the meters). Thus, for all the meters, there are ranges of frequency and amplitude over which the errors due to over-registration are smaller than the meter uncertainty but there are only very limited ranges of conditions where the error due to amplitude attenuation are not significant.

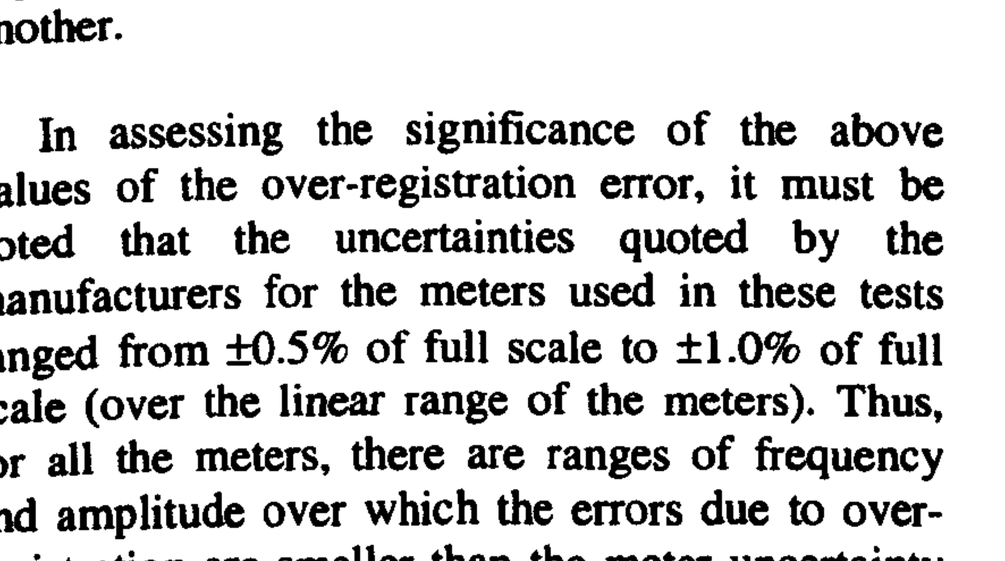


Figure 3 Comparison of true flow and meter indicated flow at 20Hz imposed pulsation with 40% relative pulsation amplitude

SIMULATION OF METER BEHAVIOUR

As indicated in the Introduction, an initial attempt to correlate the data was made using an Atkinson type model in which the meter response parameter was modified in the manner indicated by equation (3). When the modified equation (1) is normalised in the form used by Atkinson, it can be written, for a sinusoidally pulsating flow $(\dot{V}_a = \dot{V}_{a0}(1 + \alpha \sin T))$, as

$$B' \frac{dF}{dT} + F(1 + \alpha \sin T) = (1 + \alpha \sin T)^2 \qquad (4)$$

where $F = \dot{V}_m / \dot{V}_{a0}$, $B' = 2\pi b' f_p / \dot{V}_{a0}$, $T = 2\pi t f_p$ and f_p is the frequency of the pulsation.

Before equation (4) can be solved for F as a function of T, values for B' and α are required. For any given test f_p is known and α and $\dot{V}_{a0}$ can be determined from the EM flowmeter data and weigh tank data, respectively, but a value of b' is required. In all the work on the response of turbine meters in gas flows, b has been determined experimentally from step response tests, but such tests are much more difficult in water because the step must be much faster and the dynamic pressures involved are much larger. The only published reports of step tests in water are those by Cheesewright and Clark [12], which include data for two of the meters used in the current tests. For one of these meters Cheesewright and Clark also report values of b obtained by calculation from step tests with the meter in air flow and values of b obtained by calculation from engineering drawings of the meter rotor. These data suggest that

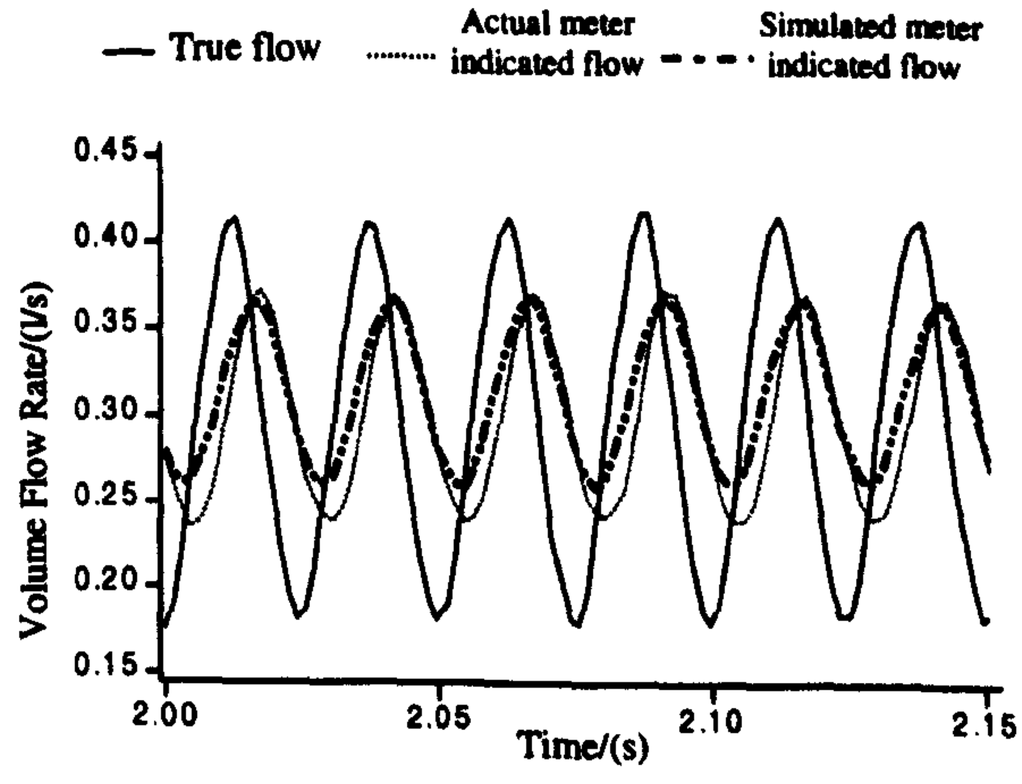


Figure 4 Meter B — Comparison of true, actual meter indicated and simulated meter indicated flow at 40Hz imposed pulsation with 40% relative pulsation amplitude

adequate estimates of the value of b' can be obtained from drawings of a meter rotor if it is assumed that only the fluid contained within the envelope of the meter rotor contributes to I_f. This approach was used to obtain values of b' for those meters which had not been subjected to step response tests.

Equation (4) was solved numerically (using Mathematica (V. 4.0.1)) and from the resulting $F(T)$ a simulated meter output can be obtained. Figure 4 shows a comparison of the simulated meter output with the actual meter output and the true flow rate (as given by a combination of the pulsation waveform from the EM flowmeter and the mean flow rate from the weigh tank) for meter B when subjected to a 40% relative amplitude pulsation at 40 Hz. Table 2 shows one example of the results of the simulations for each of the meters, expressed in terms of the over-registration and amplitude attenuation as given by the actual meter output and by the simulated meter output.

DISCUSSION

The experiments have shown that all the meters suffer from significant pulsation amplitude errors over a range of pulsation amplitudes and frequencies. The over-registration error is proportionately much smaller than the pulsation amplitude error, but is greater than the measurement uncertainty quoted by the meter manufacturers over some ranges of conditions. As might be expected, both the amplitude attenuation and the over-registration increase with increasing pulsation frequency and (slowly) with increasing pulsation amplitude.

A comparison has been made between the flow rate indicated by the observed meter output signal and that suggested by an Atkinson type simulation, based on the true (pulsating) flow rate. Figure 4 shows that the general form of the simulation appears to be correct although the simulation produces too large an amplitude attenuation and also too large an over-registration. However, the brief selection of results for different meters, reproduced in Table 2, shows some inconsistency in the accuracy of the simulation. It is not readily apparent whether this inconsistency arises from uncertainties in the values of the response parameter for the different meters or whether it indicates a need to include an additional term in the meter response equation as suggested by Dijstelbergen [11]. In a program of continuing work on the dynamic response of small turbine meters in liquid flows it is intended to attempt to determine the appropriate values of the response parameters by means of step response tests.

The results presented in this paper also serve to emphasise another feature of performance of small liquid flow turbine meters, which does not appear to have been discussed by previously. Conventionally these meters generate a signal by virtue of the turbine blades passing an electromagnetic pick-up so that the rate at which information is obtained about the rotational speed of the turbine is equal to the blade passing frequency (or slightly more than this as indicated in this paper). It is clear from the data that, physically, the meters can respond to flow pulsations with frequencies higher than the blade passing frequency (albeit, with significant amplitude attenuation), but that the normal operation of the meters does not allow information about this response to be extracted from the meter. If it was desired to exploit the response of these meters to the highest frequencies, assuming that it proves to be possible to correct for the inertia of the meter, it would be necessary to devise an alternative method for obtaining an output signal proportional to the rotational speed of the meter.

CONCLUSIONS

New data have been obtained, which demonstrate the occurrence of over-registration and amplitude attenuation when a small turbine flowmeter is subjected to a pulsating liquid flow

. Although the over-registration errors are within the limits of specified meter accuracy for low frequency pulsations they may be significant for higher frequencies and larger pulsation amplitudes. The amplitude attenuation error is likely to be significant over a considerable range of amplitudes and frequencies and can be as large as 50%. An Atkinson type model of the meter response has been investigated as a basis for a possible correction procedure and currently work is being undertaken to investigate this, and other correction procedures, further.

METER	Test Condition			Experimental Result		Simulation Result	
	Pulsation Frequency	Relative Pulsation Amplitude	Actual Mean Flowrate/(l/s)	Over-registration	Amplitude Attenuation	Over-registration	Amplitude Attenuation
A	20Hz	54%	0.095	0.74%	44%	8.68%	40%
B	40Hz	40%	0.291	3.39%	44%	6.65%	57%
C	20Hz	50%	0.096	1.66%	52%	8.38%	45%
D	80Hz	33%	0.290	1.81%	46%	3.63%	45%
E	70Hz	6.36%	1.745	0.1%	38%	0.18%	63%

Table 2 Comparison of Experimental and Simulation Results

ACKNOWLEGEMENT

The experimental work and part of the input from the second author were supported by a grant from the UK Engineering and Physical Sciences Research Council.

REFERENCES

[1] R. C. Baker, Turbine flowmeters: II. Theoretical and experimental published information, *Flow Meas. Instrum.*, 4(3), 1993, 123-144.

[2] E. Ower, On the response of a vane anemometer to an air-stream of pulsating speed, *Phil. Mag.*, 7(23), 1937, 992-1004.

[3] W. F. Z. Lee, M.J. Kirik, J.A. Bonner, Gas turbine flowmeter measurement of pulsating flow, *J. Engineering for Power, Trans. ASME*, October, 1975, 531-539.

[4] J. W. Bronner and R. J. McKee, Cogen pulsation effects on turbine metering, *American Gas Association, Operating Section, Proceedings*, 1991, 625-638.

[5] J. Grey, Transient response of the turbine flowmeter, *Jet Propulsion*, February, 1956, 98-100.

[6] W. F. Z. Lee and H. J. Evans, A field method of determining gas turbine meter performance, *J. Basic Eng. Trans. ASM*E, December, 1970, 717-728.

[7] R. Cheesewright, D. Edwards and C. Clark, Measurements with a turbine flow meter in the presence of large, non-sinusoidal pulsations, *Proc. FLUCOME '94*, Toulouse, France, August, 1994.

[8] R. J. McKee, Pulsation effects on single- and two-rotor turbine meters, *Flow Meas. Instrum.*, 3(3), 1992, 151-166.

[9] R. Cheesewright et al, Field tests of correction procedures for turbine flowmeters in pulsatile flows, *Flow Meas. Instrum.*, 7(1), 1996, 7-17.

[10] K. N. Atkinson, A software tool to calculate the over-registration error of a turbine meter in pulsating flow, *Flow Meas. Instrum.*, 3(3), 1992, 167-172.

[11] H. H. Dijstelbergen, Rotameters and turbine flowmeters in pulsation flow measurement, *Measurement and Control*, 3, December, 1970, 197-204.

[12] R. Cheesewright and C. Clark, Step response tests on turbine flowmeters in liquid flows, *Proc. Instn. Mech. Engrs.*, 211(A), 1997, 321-330.

[13] D. J. Higson, The transient performance of turbine flowmeters in water, *J. Sci Instrum.*, 42(5), 1964, 337-342.

[14] P. Jepson, Transient response of a helical flowmeter, *J. Mech. Eng. Sci.*, 6(4), 1964, 337-342.