Proceedings of ICFDP7:
7th Int. Congress on Fluid Dynamics & Propulsion
December 18-20, 2001, Cairo, Egypt

ICFDP7-2001018

USE OF FLOW SOLUTIONS IN HIGHLY RESISTIVE MEDIA TO IMPROVE BFCS FOR COMPLICATED GEOMETRY

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ABSTRACT

The paper presents a simple and effective procedure for generating highly orthogonal boundary-fitted-coordinate grids, which are superior to those generated by the solution of Poisson type equations, built into most commercial computer codes. The method is based on solving for the flow in a highly resistive porous media filling the inside or outside of the geometry to be fitted. The resulting streamlines and pressure contour lines, form an orthogonal network which is used to derive the boundary-fitted-coordinate grid lines. The method is applied to generate the grid required to predict the flow inside a complicated S-shaped duct, and the flow both over and within a venturi like duct; a highly improved grid was obtained in both cases.

INTRODUCTION

In many fluid flow predictions of real world engineering problems the geometry considered does not lend itself to expression by regular Cartesian or polar coordinate grids. Accurate expression of boundary conditions in these cases requires the adoption of boundary fitted coordinates, BFC. In general, it is desirable to have the BFC as orthogonal as possible, since non-orthogonality of the grid lines introduces additional terms in the discretized equations, leading to an increase of computational time, reduction of accuracy and slower convergence. For example, the production term for the kinetic energy of turbulence[1], appearing in many turbulence models, requires the evaluation of 9 individual terms if the grid is orthogonal , while it requires the evaluation of up to 81 such terms if the grid is non-orthogonal.

Conventional methods for generating BFC derive the Cartesian coordinates of the control volumes corner points by solving non-linear elliptic equations for those quantities[2-8]. The linearized forms of these equations, which are of the Poisson type, are solved iteratively, updating the coefficients after each solution, until a well converged solution to the non-linear equation is obtained.

Much research has gone into improving the orthogonality of the grid resulting from the solution of these equations, and highly orthogonal grids are displayed for many idealized conditions. However in practice they are not always successful at producing desirable grids, the resulting control volumes being either too non-uniformly distributed, or non-orthogonal , or both, as will be demonstrated in the examples to follow.

The paper presents a procedure for yielding desired grids which display high orthogonality in troublesome cases. The method is highly flexible and can be easily incorporated in almost any fluid flow simulation program which provides a facility for generating a BFC grid and allows an external BFC grid file to be read. Although it requires some manual intervention, this requirement also allows more control on the produced grid features.

Two demonstration cases have been selected which demonstrate the application of the method. The first features a purely internal flow , and the second an internal-external flow.

THE PROCEDURE

It is always possible to derive a potential flow solution for the problem at hand. This solution is easy and quick to obtain , since it requires the solution of a single linear Laplace equation for the potential function, φ or stream-function, ψ. The resulting streamlines and equi-potential lines constitute a network of orthogonal lines. If the potential flow solution is obtained for flow over or within the same geometry as the one for the viscous / turbulent flow to be predicted, then some of the predicted streamlines would outline the boundary shape of the geometry. Thus the computed network of streamlines and equi-potential lines could serve as an orthogonal BFC grid fitting the desired geometry.

However, not all available codes designed to solve viscous and turbulent flows are also equipped to solve potential flows. Hence, in order to make the method as widely applicable as possible, solutions are obtained for flows in highly resistive porous media instead of potential flow. The streamlines and constant pressure lines obtained from the former solutions also display orthogonal sets of lines, which are similar to those of potential flow. Since wall boundaries are impermeable, they also constitute streamlines; therefore the resulting orthogonal set can be made to generate BFC grid lines .

Almost all three-dimensional BFC grids are generated employing two-dimensional BFC grids over several surfaces, with some form of interpolation for the coordinates in between. The same approach will be followed here; thus the method will be presented for a single surface grid, i.e. in two dimensions.

The equations for flow in a two-dimensional, highly resistive porous media, are:

$$C_f\ v = \partial p/\partial y \qquad (1)$$

$$C_f\ w = \partial p/\partial z \qquad (2)$$

where C_f is the coefficient of friction, v and w are the velocity components in the y and z Cartesian coordinate directions respectively. Equations (1-2) may be combined in the following vectorial form:

$$\underline{V} = \underline{\nabla}\ (p/C_f) \qquad (3)$$

where $\underline{\nabla}$ is the gradient operator and $\underline{V}$ is the velocity vector whose components in the y and z directions are v and w , respectively.

Equation (3) reveals that (p/C_f) is the potential function whose gradient is the velocity vector. Provided the appropriate boundary conditions are introduced, the solution of the above equation for $\underline{V}$ is the same as the potential flow solution obtained by solving Laplace's equation for the potential function. Moreover, the constant pressure lines are orthogonal to the streamlines obtained from the computed velocities.

If the software used does not provide the option of solving for the flow in highly resistive porous media, nor does it allow the switching-off of diffusion and convection terms , the solution for highly resistive flows may still be effected by introducing the porous-media resistance term and setting C_f to a large value(say 10^4), while ensuring through appropriate boundary conditions that the stream wise velocity is of the order of one.

Thus the proposed BFC generation procedure is as follows:

1- The BFC option of the available fluid simulation program is employed to generate a preliminary BFC grid, for the considered geometry.
2- The appropriate boundary conditions are set for highly resistive flows and eqn(3) is solved numerically.
3- The corresponding streamlines and constant pressure-lines are derived and plotted. The points of intersection of the streamlines and the constant pressure lines correspond to the control-volumes corners in the considered plane. The number of cells and the spacing between the grid lines are controlled by selecting the numbers and values of the pressure-contour-lines and streamlines.
4- Once a convenient orthogonal network is displayed, the coordinates of the intersection points are recorded. It may be necessary to introduce manually some additional streamlines or pressure contour lines, so as to make the BFC grid more appropriate. As long as a sufficient number of computed streamlines and pressure contour-lines are displayed, it should be possible to interpolate graphically intermediate lines with high accuracy.

The method is best described by way of example; two demonstration cases are now presented.

FIRST DEMONSTRATION CASE

This case involves the generation of a BFC grid for an inlet duct to a HRSG, presented in [9]. The full integration domain includes an S-shaped inlet duct, the HRSG and the chimney stack, Fig.1; however, attention here will be focused on the grid distribution in the inlet duct and HRSG alone, as this is the troublesome part of the grid.

Figure 2 displays the BFC grid obtained by the conventional procedure, i.e. solving the quasi-Poisson equations for the control-volumes corner-coordinates. The grid is seen to be fairly orthogonal; however, in 2 regions the control-volumes are too tightly packed, and in one of them the grid lines are severely squashed. This affects accuracy of predictions as the unduly high concentration of control volumes in a section of the domain , implies a reduction of control-volumes elsewhere. Moreover, the very large area ratios of such control volumes cause the coefficients of the discretization equations to be much larger in one direction than the other . If the SIMPLE procedure[10] or one of its variants is employed to solve the set of discretized equations, the large difference in the magnitude of the pressure-correction equation coefficients causes convergence problems.

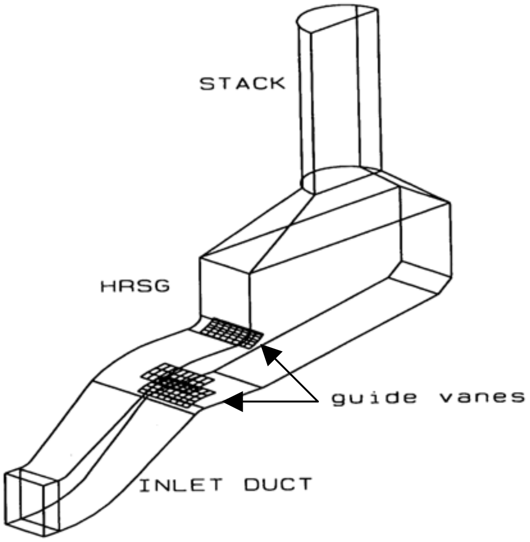

Figure 1. Inlet duct, HRSG and chimney stack.

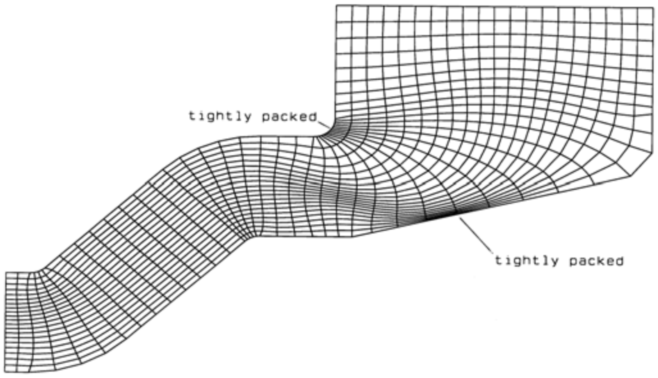

Figure 2. Original BFC grid

To derive a better BFC grid, we start by solving the governing equations for flow in a highly resistive porous media, employing the previous BFC grid and the following boundary-conditions:.

i - Inlet boundary:

A uniform inlet pressure, and zero cross-stream velocity are specified at this boundary. The stream-wise velocity is determined by the solution.

ii- Exit boundary:

A uniform exit pressure, and zero cross-stream velocity are also specified at this boundary. The difference between the inlet and exit pressures depends on the length of the duct and the value of C_f ; it should be specified such that it causes a stream-wise velocity of order close to one, to reduce rounding off errors.

iii- Wall boundaries:

Impermeable wall conditions are imposed at these boundaries.

It is remarked that pressure type boundary-conditions are preferred to streamwise-velocity boundary conditions at the inlet/exit sections. This is because the former produce pressure contour lines parallel to the inlet/exit boundaries, whereas the latter do not. This has an important bearing on the grid generated, since pressure contour lines form one set of the BFC grid lines.

Figure 3 displays the velocity vectors calculated for the flow inside the duct filled with highly resistive porous media.

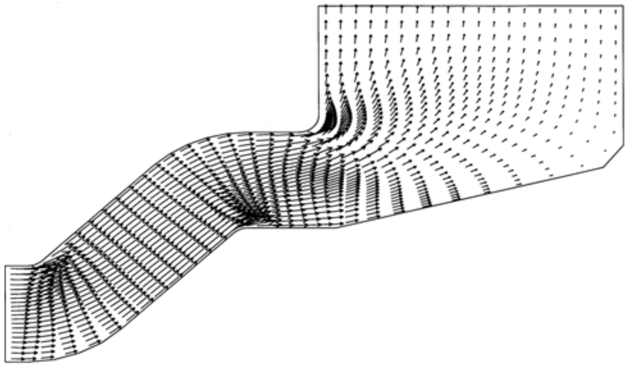

Figure 3. Velocity vectors for flow in highly resistive media.

Figure 4 displays the corresponding streamlines and pressure-contour lines. These were created employing the built in facilities of the software. The stream lines were initiated at the inlet end of the duct, at approximately equal vertical spacing. The pressure-contour lines were created by prescribing equal pressure intervals; however, smaller intervals were employed in regions of small pressure gradients, in order to yield the required density of lines.

Figure 4 displays a highly orthogonal and desirable BFC grid; a considerable improvement over that displayed in Figure.2. It must be emphasized here, that the displayed intersection points do not necessarily generate the control volumes of the BFC grid. Provided a sufficiently fine network is displayed, it is a simple task to interpolate graphically new grid lines and select the desired control volume control points. Also, the pressure contour lines need to be extended all the way to the walls to yield the corner coordinates at the wall boundaries.

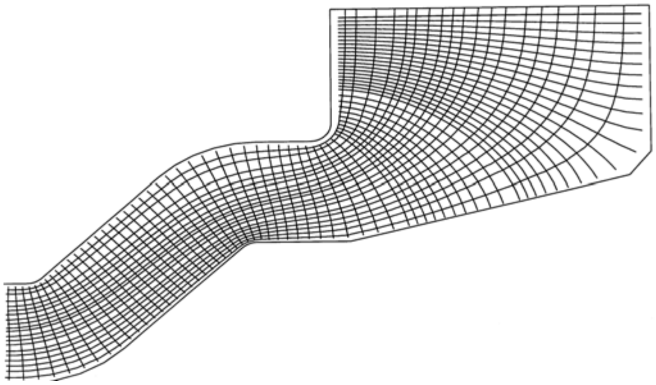

Figure 4. Streamline –pressure contour line network

In this particular application[9] it was required to design internal guide vanes, Fig.1, whose shapes conform to the local potential flow streamlines. Had a set of grid lines been the streamlines(proposed method), it would have facilitated tremendously the expression of the guide vanes boundaries, and reduced the time required to set-up each trial.

SECOND DEMONSTRATION CASE

This case was derived from the problem of designing a wind activated ventilation device, [10]; a sketch of the device is displayed in Fig.5. The problem involves the prediction of the flow both inside and outside the device, i.e. both internal and external flow. To facilitate the construction of the BFC grid, the integration domain is split into 2 parts, a top part and a bottom part. The interface surface follows the contours of the top wall of the device, approaching it and leaving it horizontally.

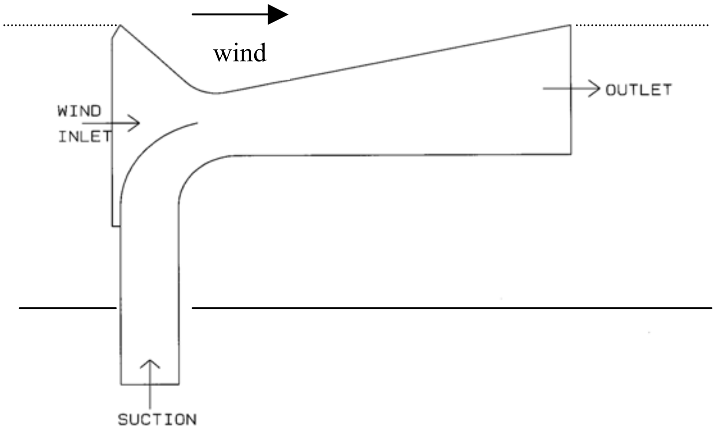

Figure 5. The Wind-driven Air extractor, [10].

First the top part of the integration domain is considered. The BFC grid created by the conventional method is displayed in Fig.6. The grid is quite orthogonal; however, the control volumes are severely squashed in the region of the venturi section.

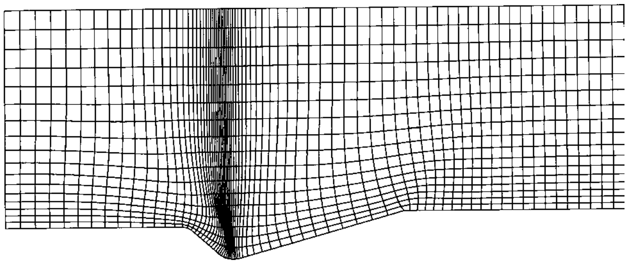

Figure 6. Original Wind-ventilator BFC grid in top part.

To generate the improved BFC grid, the flow in a highly resistive media filling the top part of the integration domain is computed. The boundary conditions for this flow, feature uniform inlet and exit pressure boundary-conditions, and impermeable wall-conditions at both the top and bottom boundaries. Figure 7 reveals the network of streamlines and pressure-contour lines produced from this solution. Comparison against Fig.6, reveals the disappearance of the squashed control-volumes, and a much more favorable grid distribution.

Figure 8 reveals an enlargement of Fig.7 centered about the venturi section. As an exercise for demonstration purposes, the pressure contour lines have been extended all the way to the wall, and 4 additional contour lines have been plotted manually employing graphical interpolation, in order to increase the resolution in this region.

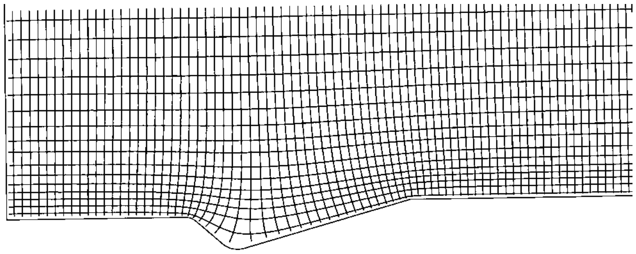

Figure 7. Streamlines & pressure-contour-lines network

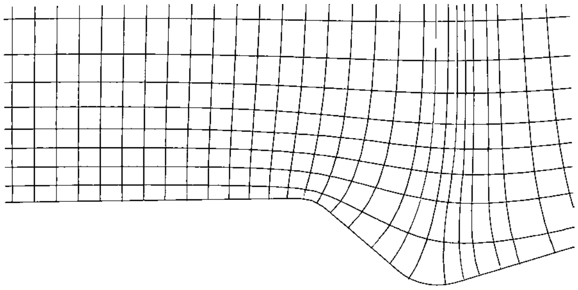

Figure 8. Enlargement and additions to previous figure.

Secondly the bottom part of the integration domain is considered. Fig.9 displays the BFC grid created by the conventional method; three regions of highly irregular and squashed control-volumes appear close to the inlet of the device; elsewhere the grid distribution is acceptable.

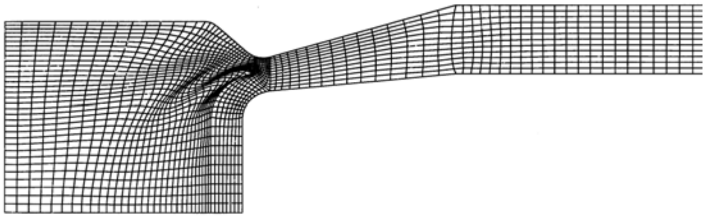

Figure 9. Original Wind-ventilator grid in bottom half.

In order to generate an improved grid, the flow in a highly resistive media filling the bottom part of the integration domain is computed. The boundary conditions for this flow employ uniform inlet/exit pressure boundary-conditions at the inlet/exit boundaries, respectively. However, the presence of two inlets requires the specification of 2 inlet pressures. The relative magnitudes of their pressures affects the flow pattern and hence the generated grid. This added complication resulting from multiple inlets, also introduces a degree of freedom, as many different *orthogonal* grids may be produced for the same geometry, and the most suitable is selected. The author found that for the problem considered, a good grid distribution was obtained with the bottom inlet pressure about 20% higher than the side inlet pressure. It must be noted here that there is no connection between the flow in the highly resistive media and the flow to be predicted with the BFC grid; it is the boundary geometry only that needs to be identical.

In addition to inlet/outlet conditions, impermeable wall-conditions are applied at all device walls, as well as at the top and bottom surfaces.

Figure 10 reveals streamlines and constant pressure lines resulting from the flow in porous media predictions; it is seen to present a highly orthogonal network. In order to display clearly the wall boundaries, streamlines are not drawn close to walls, and some are not extended to their full length.

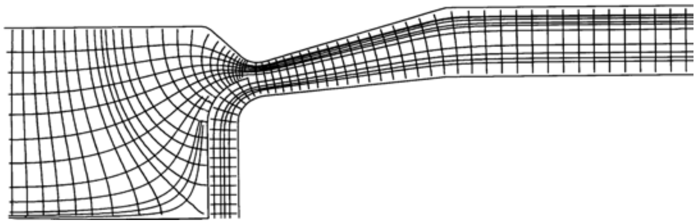

Figure 10. Bottom half streamlines & pressure contour lines.

Figure 11 reveals an enlargement, in which pressure contour lines have been extended to walls and a few extra interpolated lines plotted. One of them, appearing dashed, displays the interpolated extension of the internal wall streamline. It is remarked that at the internal partition the pressure contour lines do not necessarily meet. However, it is always possible to plot manually appropriate grid lines interpolated between adjacent pressure contour-lines. Indeed it is recommended to free oneself from the actual intersection points of the stream lines and pressure contour lines and to plot desirable grid lines guided by the displayed orthogonal network; provided one is careful, deviation from orthogonality should be negligible.

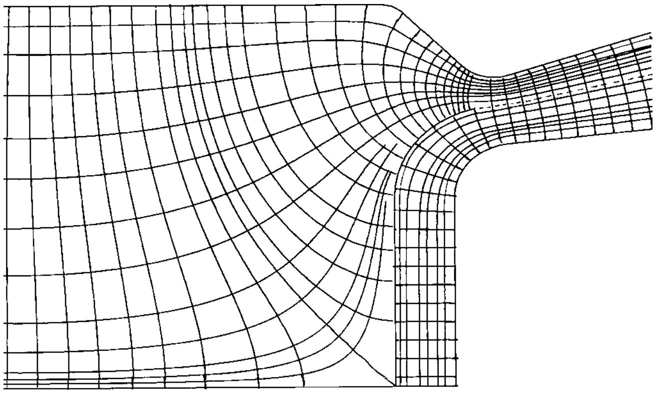

Figure 11. Enlargement and additions to previous figure.

SUMMARY & CONCLUSIONS

The paper presents a procedure for generating BFC grid lines who are highly orthogonal and orderly. The method is designed to be easily introduced into existing software packages with BFC capabilities. It makes use of the built in BFC feature and solution algorithms to obtain a solution for the flow in highly resistive media filling the considered geometry. The resulting streamlines and constant pressure lines are then employed to generate the desired BFC grid.

The method requires considerable manual intervention; however, it is extremely flexible and allows the user a high degree of control in structuring his grid, contrary to the automated grid generation procedures. When applied to generate 3 different BFC grids, it produced highly orthogonal and desirable grids, a considerable improvement over the conventionally generated ones. The method is also equally applicable to both external and internal flows.

It is recommended for troublesome cases where the grid generated by the software program is not acceptable, and or more control on the grid distribution is required. It is also highly recommended for the design of internal guide-vanes, and similar applications were knowledge of the corresponding potential flow is required.

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