A GEOMETRIC MODELLER FOR TURBOMACHINERY APPLICATIONS

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This paper describes a software package tailored for the geometric modelling of turbines, as well as for the automatic generation of a body-fitted coordinate grid. The package consists of four programs used respectively for:

1. The creation and the modification of a model; the designer can "edit" the model by means of commands whose basic entities are points, profiles, blades, the hub and the shroud.

2. The refinement of the model by the distribution of points over each profile defining the blade, and then by the interpolation of new intermediate profiles between the hub and the shroud.

3. The construction of surfaces delimiting the blade-to-blade channel boundaries (the computational domain).

4. The calculation of a body-fitted coordinate system, inside the channel, by the solution of a system of differential equations.

A set of modelled turbines is shown to illustrate the results of each step.

INTRODUCTION

The design of highly efficient hydraulic turbines necessitates modern and efficient tools to assist the designer in his work. He must indeed reconcile contradictory requirements regarding performance and cost, the size and the machine's reliability.

We distinguish three steps in the design approach:

1. The creation of a model for the turbine.

2. The solution, on this model, of the differential equations that describe the behavior of the fluid flow (Navier-Stokes equations).

3. The analysis of these results in light of the previous designs.

This work presents the first of the above three steps. It consists in part of the development of a software package used for the geometric modelling and the automatic grid generation for subsequent steps as a mesh for the numerical simulation of the flow phenomena.

The actual production of the modelled turbines will hence be possible using a minimum of testing and, consequently, will reduce financial risks as well as others, given an indepth study with the aid of the computer.

DEFINITION OF MODELLED OBJECTS

A turbine is composed of three main elements: the blades, the hub and the shroud. Essentially, the blades being all identical, the definition of one suffices.

The main objective of the modelling process is to create a geometrical representation of these objects in such a manner as to render them accessible to users for purposes of analysis and visualization or for modification (geometric modelling).

A second main objective, once the shape has been created, is to prepare the physical flow domain for purposes of fluid dynamics calculations (computational modelling).

This, when using numerical methods for the solution of differential equations, requires the usage of a mesh. In the present software package, this step is carried out automatically and the resulting mesh is a curvilinear coordinate system which fits the domain boundaries.

This domain is a closed volume, referred to as a "blade-to-blade channel", extending from one blade to the next, from hub to shroud and, by extending the blade length, from the inlet plane of the turbine to the outlet plane. These extensions result in two "ruled surfaces" extended from each side of the blade towards the inlet and outlet planes. For convenience, we shall refer to the set of the surfaces bounding the channel as the "shell".

CHARACTERISATION OF ELEMENTS AND DATA STRUCTURE

The blade can easily be represented by a surface folded upon itself in a three dimensional space; the blade being bounded by the hub and the shroud. This surface can be characterized by two sets of lines: the first, traversing from the hub to the shroud, and the second set going around the blade. These two families of curves form a grid where the intersection of one line of a family with that of another results in a node (Fig. 1). These points serve as a base for defining the blade by means of interpolation. Other representations of the blade such as solid hexahedrons or bi-dimensional "patches" are also possible, but would be less suitable for the modelling methods employed here.

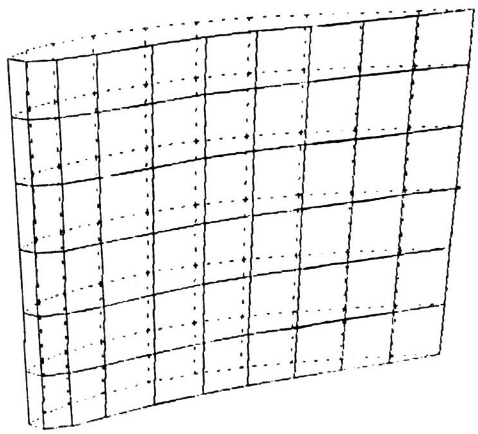


Fig 1. Characterisation of a blade

The characterisation of the blade permits the use of a well known concept in this domain, that of a profile. A profile is a cross-section along a given surface that is located between the hub and the shroud. These profiles consequently form one of the families of curves characterizing the blade and are defined by interpolation of the coordinates of known points, by means of cubic splines parametrized with respect to the arc length.

The hub and shroud are described by surfaces of revolution (Fig 2); it is therefore sufficient to define, for each, a curve in a given plane and an axis of revolution.

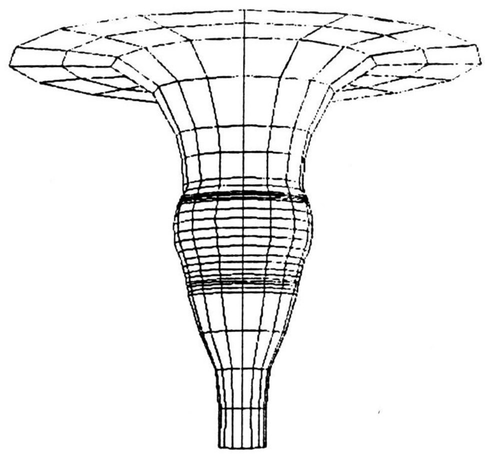


Fig 2. Definition of the hub

Finally, we should mention that no profile is explicitly defined at the surface of the hub or at that of the shroud; it is by extrapolation that an extension of the blade is computed up to the intersection with the hub in one direction, and with the shroud in the other. This allows the modification of the hub and shroud independently of the profiles at the extremities of the blade. It is with the addition of the above mentioned profiles to the previously defined profiles that we find, by interpolation of their points, the second set of curves running from hub to shroud.

The database stores the necessary elements for the geometric description of four categories of "objects":

1. The non-refined version of the turbine: the profiles, the hub and the shroud.

2. The refined version of the turbine: the profiles (the "natural" points), the hub and the shroud.

3. The shell (computational domain boundaries).

4. The body-fitted curvilinear grid.

These files form the sole links (input/output) whereby information is transferred between the functional modules.

THE COORDINATE SYSTEMS

The design process can be carried out in one of three different referentials: cartesian (x,y,z), cylindrical (r,θ,z) and toroidal (R,θ,ϕ), as shown in Fig 3,4 and 5. A certain similarity in their use is established if we agree, for all systems, that their coordinates indicate respectively the distance from the hub to the shroud, from one blade to the next and from the inlet plane to the outlet plane. The programs take advantage of this convention and perform all of their operations, in a general manner, on coordinates one, two and three, without ever really considering the actual referential. Rather it is the user who interprets the results appropriately, according to the coordinate system that he chooses to use; a displacement in the direction of one of the coordinates can hence be considered as a rotation or as a translation (depending on whether the coordinate is an angle or not). The application of certain functions may at times seem disconcerting in certain referentials, but do however appear natural enough once their mechanics are understood.

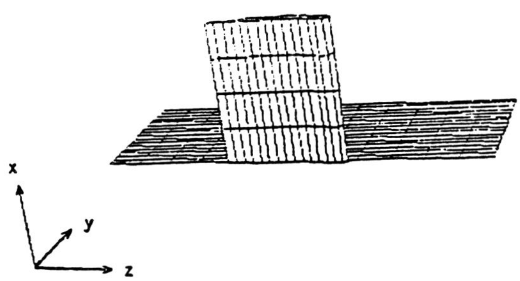


Fig 3. Cartesian coordinate system

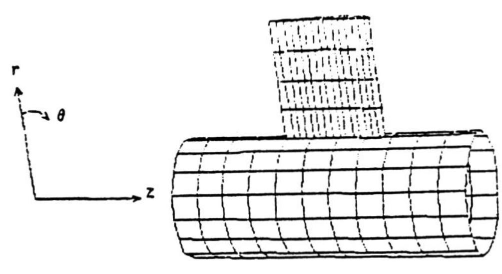


Fig 4. Cylindrical coordinate system

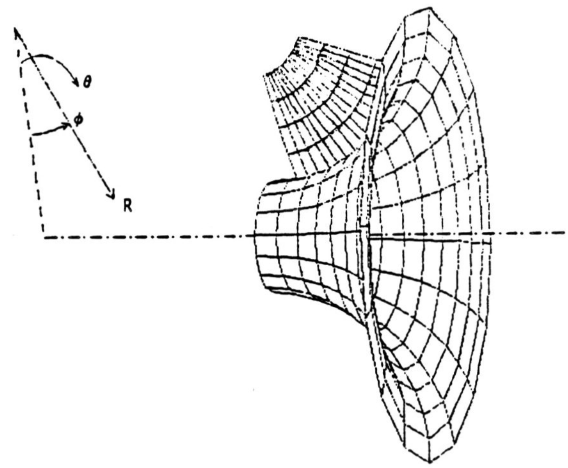


Fig 5. Toroidal coordinate system

SCREEN DISPLAY

The display and modification of three-dimensional objects on a graphic terminal having only two dimensions undoubtedly causes problems. The visualization of 3-D objects by means of various projections is thus necessary and succeeds in rendering rather completely the true geometric characteristics of these objects. The inverse communication that is from the designer to the program is more difficult, because the dialogue is restricted by the physical devices such as the flat screen, cursor, pen, mouse, etc. These do not allow for the passage of all the geometrical data that we would desire: only two dimensions can be input to the program at one time, due to the absence of true depth at the screen. Thus, to develop an acceptable method of communication, one must judiciously combine their use with that of a particular projection.

We can easily project the blade profiles on three different surfaces, each corresponding to a constant value of each coordinate (orthogonal projection). This type of projection, because of the speed and ease with which it can be implemented was retained. This stems from the fact that one of the coordinates is simply dropped while displaying the other two. The creation and modification of profiles is easily made because the screen's surface corresponds to two of the profile's dimensions.

THE PROGRAMS

THE DESIGN OF A MODEL

This first program deals with the geometric modelling and modification aspects of the turbine. A menu, displayed on the screen, lists the available editor commands; Fig 6 gives such an example.

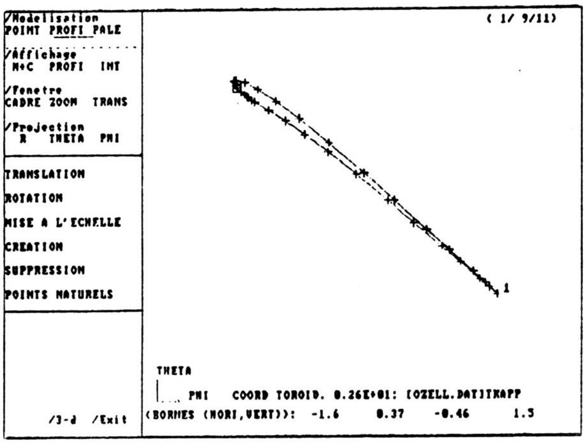


Fig 6. Typical menu for the geometric modelling

These commands fall into four categories:

1. Those whose basic entity is a point (they are performed with the aid of the graphic cursor):

   - The creation and insertion between other levels of a new profile. Points are entered on the screen on a constant coordinate surface.

   - The modification of either profiles or curves representing the hub and the shroud, by adding, deleting, displacing, duplicating or permutating the points that define them.

2. Those whose basic entity is a profile:

   - scaling

   - translation

   - rotation

   - the addition of profiles by duplicating them

   - the rearrangement of profiles by moving their order around

   - deletion.

3. Those who deal with reading or writing the model's geometry in a given file (file and data management) and whose basic entity is the entire model.

4. Those dealing with visualization of the model:

   - the choice of a projection to display a profile

   - the choice of the displayed element (pointer to a profile, the hub or the shroud) as well as the interval of profiles to display along with the chosen element, and the presence or not of the hub and the shroud

   - the display of all profiles at one time in a three-dimensional cartesian frame of references for a better grasp of the turbine's actual shape (with possibilities of rotating the model with respect to the three axes)

   - the modification of the display window by translations, by specifying two new corner points, or by allowing the program to automatically calculate one

   - the choice of the symbol's size (i.e. the points identifier).

   - the choice of the number of line segments joining two consecutive points for the curve's approximation

   - the possibility of refreshing the display when too much obsolete data appears on the screen, or simply to visualize the result of a modification to an element

Certain pertinent information is always listed within the screen's frame:

- the profile's number currently displayed (upper right-hand corner)

- a coordinate dyad indicating the coordinates used for the projection (lower left-hand corner)

- the referential used

- the edited file's name.

- the physical values corresponding to the screen's frame boundaries.

THE REFINEMENT OF THE MODEL

This second program allows the refinement of the geometrical definition of the turbine. This process permits a description with a greater number of points, and/or mainly with a new distribution as a function of the local curvature. Afterwards, we refine the blade by creating supplementary intermediate profiles by means of interpolation between the hub and the shroud.

The same functions mentionned above are available in addition to those relevant to the refinement of the model which are in three steps:

1. Firstly, an equal number of points are "naturally" distributed on each profile in proportion to its local curvature. The curvature is calculated in two dimensions with respect only to the two last coordinates in order to avoid consideration of the first coordinate's influence (oriented hub to shroud). Concentration is controlled by one parameter specified by the user.

2. Secondly, these new points are then used to automatically create, by means of extrapolation, two profiles at the intersection of the blade with the hub and shroud.

3. Lastly, new intermediate profiles are generated by means interpolation between the hub and the shroud.

The original profiles, the refined profiles or the intermediate refined profiles can be displayed in a three-dimensional cartesian system using the previous functions.

THE CONSTRUCTION OF A SHELL

The shell is made up of the pressure side and the suction side of two consecutive blades, four ruled surfaces, the inlet and outlet planes, the hub and the shroud, as shown in Fig 7.

It is constructed in two steps:

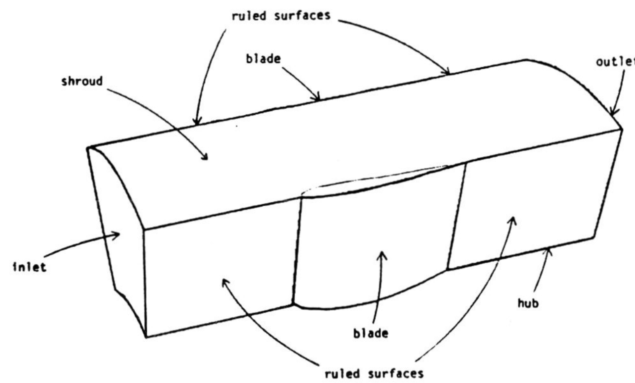


Fig 7. Definition of the shell bounding the computational domain

1. The limits of the ruled surfaces are defined by extending edges from the leading (trailing) edge of the hub and shroud profiles. These lines lie on the surface of the hub and the shroud, going from the blade to the inlet (outlet) plane. The angles and lengths of these lines are specified by the user. Points are then distributed along the lines according to a concentration parameter, also given by the user.

2. By providing the number of blades of the turbine, the user indirectly provides the blade-to-blade channel distance i.e. the width of the shell. The concentration and the number of points in the blade-to-blade direction are given by the user.

The program automatically performs all the functions related to the display (window calculations, for example), and its execution is sequential.

THE GENERATION OF A BODY-FITTED CURVILINEAR COORDINATE GRID

The approach proposed by certain authors [1,2] for creating a three-dimensional body-fitted coordinate system consists of solving a system of three coupled non-linear elliptic equations. These equations describe the transformation undergone by a cartesian regular mesh in a parallelepiped prism which would be stretched and deformed until it is adapted to the channel. We hence define a relation that enables us to introduce the curvilinear coordinate system.

This transformation of the domain of computation simplifies subsequent calculation by the use of simple finite differences. It also allows a proper application of boundary conditions of fluid mechanics while rendering possible the control of the concentration of the nodes.

RESULTS

The described software was written in FORTRAN-77 and the TCS graphic language was used for the display within the package. For more elaborate displays (hidden lines and color), a translation routine is available which writes the data structure in the MOVIE.BYU format.

These programs were tested and applied for the modelling of practical applications to illustrate the package's applicability and range of use. They have been used with a variety of models ranging from FRANCIS and KAPLAN to bulb turbines. Fig 8(a) shows the hub and the shroud of a FRANCIS turbine, in a toroidal system, while Fig 8(b) shows a bulb turbine, in a cylindrical system.

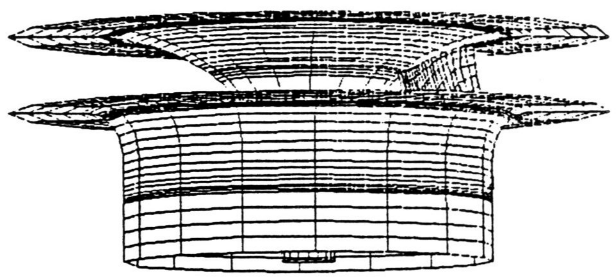


Fig 8(a). Modelled FRANCIS turbine

The next step is to construct a shell bounding the computational domain. The one corresponding to the FRANCIS turbine is shown in Fig 9. The inlet plane and a part of the hub are visible in Fig 9(a), while Fig 9(b) depicts another view of the same channel after a 160 degree rotation around the central axis. Fig 10 shows the shell constructed for the KAPLAN turbine. Fig 10(b) depicts the same object as Fig 10(a), after a 180 degree rotation, and allows us to see the inlet and outlet planes.

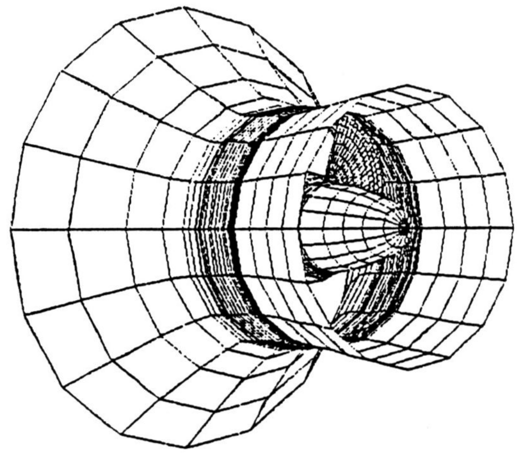
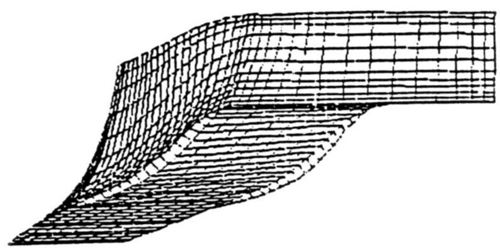
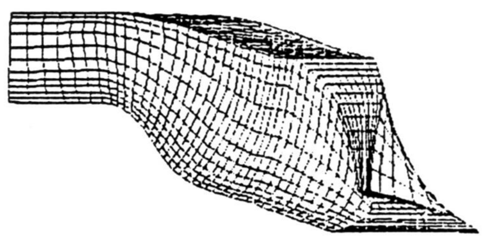


Fig 8(b). Modelled bulb turbine



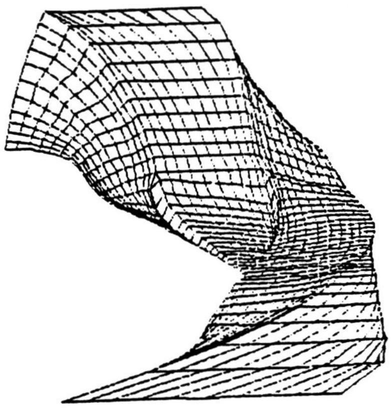
9(a)



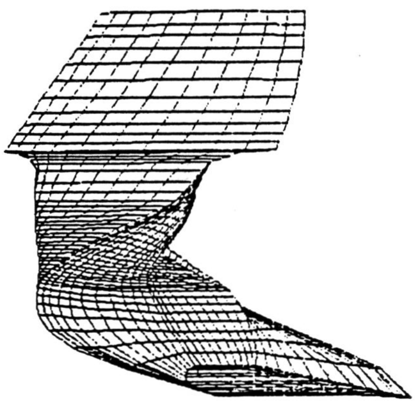
9(b)

Fig 9. Three dimensionnal projections of the shell for the FRANCIS turbine.

Figs 11 and 12 show the body-fitted coordinate system generated automatically within the shells. The coordinate surfaces lying between the hub and the shroud or the ones that are between the inlet and outlet planes are displayed. Fig 11 gives the same view angle as in 9(a), while Fig 12 corresponds to the one in 10(a).



10(a)



10(b)

Fig 10. Three dimensionnal projections of the shell for the KAPLAN turbine.

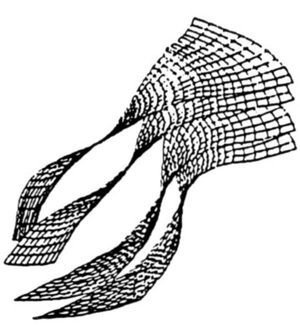


Fig 11(a). Hub-to-shroud curvilinear coordinate surfaces (FRANCIS).

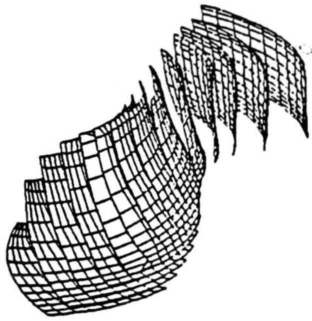


Fig 11(b). Inlet-to-outlet curvilinear coordinate surfaces (FRANCIS).

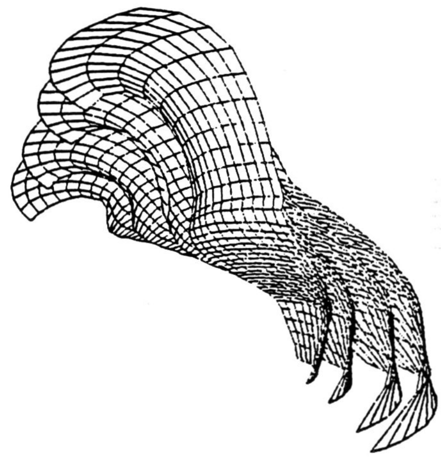


Fig 12(a). Hub-to-shroud curvilinear coordinate surfaces (KAPLAN).

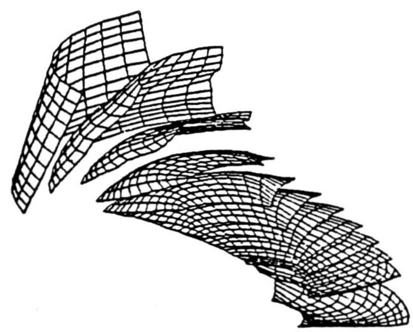


Fig 12(b). Inlet-to-outlet curvilinear coordinate surfaces (KAPLAN).

The color and transparency capabilities of the software package MOVIE.BYU have been used to produce the following pictures. Fig 13 and 14 show the modelled FRANCIS and bulb turbines with a full set of blades, in order to render a more realistic view of the actual turbines. Fig 15 shows the shell constructed for the KAPLAN turbine, along with an almost transparent hub.

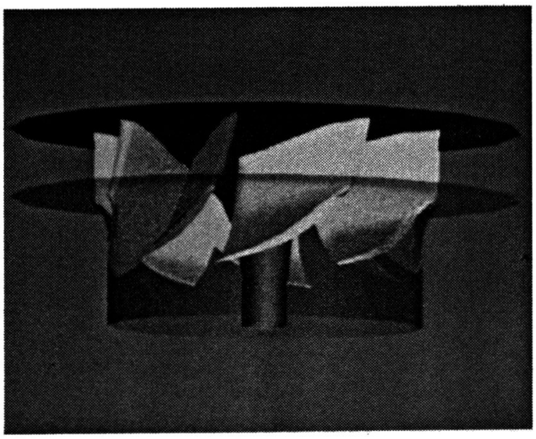


Fig 13. Modelled FRANCIS turbine with 8 blades

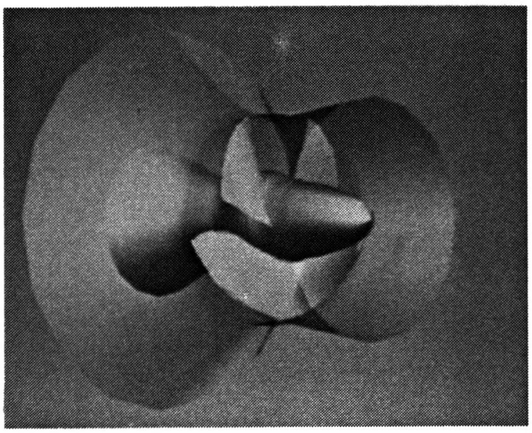


Fig 14. Modelled bulb turbine with 4 blades

After extensive use, it has been concluded that these programs work well, are reliable and user-friendly. Furthermore, they require relatively little resources, and give a very good level of interactivity. Besides being very well suited to turbomachines, one can envisage applications to other fields such as pumps, and ship hulls (Fig 16 shows such an example where a keel has already been modelled by the present programs).

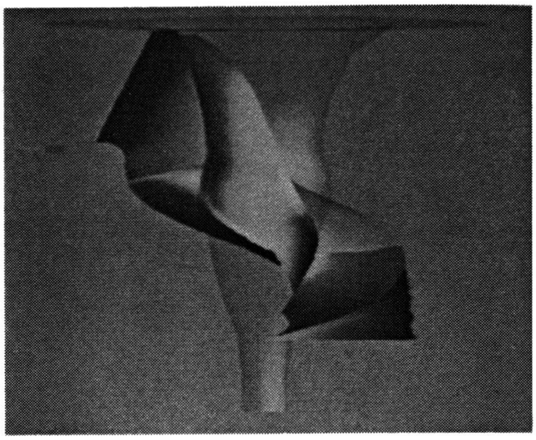


Fig 15. View of the shell constructed for the KAPLAN turbine

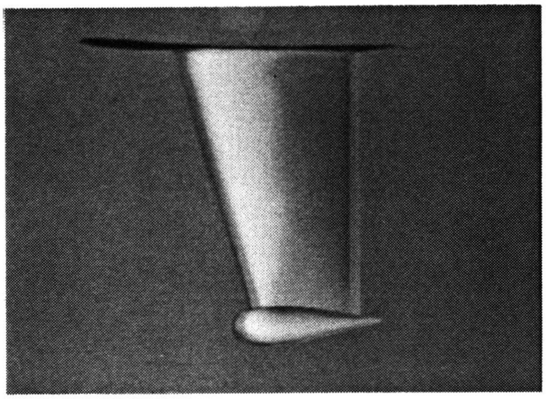


Fig 16. Modelled ship hull

1. Thompson, J.F., "Numerical Solutions of Flow Problems using Body-fitted coordinate systems", Lecture Series 1978-4, Computational Fluid Dynamics, March 13-17, 1978.

2. Camarero, R., Reggio, M., "Three-dimensional Body-fitted coordinates for Turbomachine applications", Computers in Flow Predictions and Fluid Dynamics Experiments, Ed.: K.N. Ghia, T.J. Muller and B.R. Patel, pp 51-57, 1981.