Fermilab

TM-904
2043.000

COMPUTER PROGRAM "SUPERFISH" FOR CYLINDRICALLY SYMMETRIC RF CAVITIES

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September 24, 1979

Abstract

The computer program SUPERFISH is a brainchild of Klaus Halbach at Berkeley. It calculates resonant frequencies, fields and other quantities of fundamental and higher modes for any kind of cylindrically symmetric geometry. The original code was developed by R. F. Holsinger but the one which is presently available at Fermilab on NOS is the LASL version with many convenient features added for interactive usage. This report is intended to be a simple manual for potential users at Fermilab. Those who are curious about the physics and mathematics of the program are advised to consult the following reports:

1. K. Halbach and R. F. Holsinger, Particle Accelerators, 7 (1976), p. 213.
2. K. Halbach, R. F. Holsinger, W. E. Jule, and D. A. Swenson, Proceedings of the 1976 Proton Linear Accelerator Conference, Chalk River, Canada, AECL-5677, p. 122.

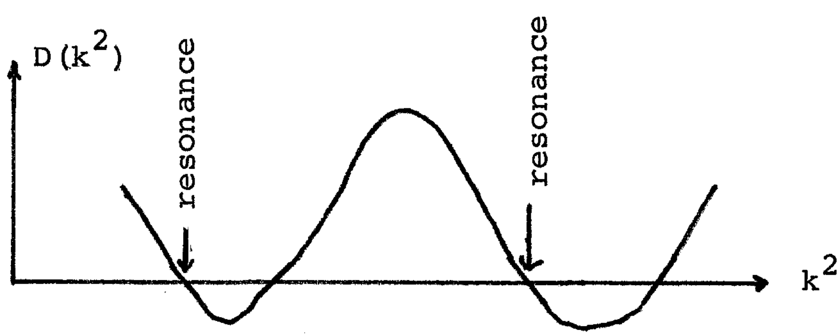
The program is especially useful for RF cavities of linacs but it has been used extensively for many types of RF power amplifiers and for the design of permanent magnets. With some tricks, it can be used for structures which are not cylindrically symmetric but with no variation in the z-direction of the cylindrical coordinate system. SUPERFISH is now generally considered to be the most powerful of this class not only in this country but also in Europe and in Japan.

Introduction*)

Almost all computer programs that have been developed over the last twenty years or so for cylindrically symmetric rf cavities try to solve a set of homogeneous linear equations using overrelaxation methods.[1] One starts with an initial loading of the field, which is often just the field of an empty cavity, and iterates until the convergence in the resonant frequency is reached. For some geometries, for example low velocity cells of Alvarez linac cavities, the convergence rate is painfully slow and the frequency is not always as accurate as one desires.[2] The ingenious idea of Klaus Halbach for SUPERFISH is to introduce a driving magnetic current in the cavity. For a given frequency, this leads one to a set of <u>in</u>homogeneous equations that can be solved for the necessary driving current withous any iteration. The problem is then reduced to one of making this current vanish by choosing a suitable frequency. In order to simplify this search procedure, Halbach defines a function $D(k^2)$ of $k = 2\pi/\lambda$. D vanishes when the driving current goes to zero but it does not depend on the scaling of the current. The function $D(k^2)$ has the property that, at the resonance,

$$D(k^2) = 0 \quad \text{and} \quad dD/d(k^2) = -1.$$

Between every two adjacent resonant frequencies, there is one root of $D(k^2)$ with $dD/d(k^2) = +1$.



SUPERFISH calculates resonant frequencies, fields and other quantities of fundamental and higher modes for almost any kind of cylindrically

*) This is an oversimplified and quite incomplete description of the program. See two reports cited in the abstract.

symmetric geometry. Boundaries are assumed to be a combination of straight lines and circular arcs. The program generates irregular triangular meshes and establishes a set of inhomogeneous linear equations. Boundary in the r direction of the cylindrical coordinate system r,ϕ,z is the symmetry axis $r = 0$. In the z direction, boundaries are either two end walls or some symmetry planes z = constant. It is of course advisable to make use of these symmetry planes whenever possible in order to save the computing time. For fields that do not depend on ϕ, two independent sets of solutions exist, that is, TM-mode (H_ϕ, E_z, E_r) and TE-mode (E_ϕ, H_z, H_r).[3] Almost all cavities used for acceleration are operated in TM-modes, E_z being responsible for the acceleration, and SUPERFISH treats the field as a TM-mode. It is of course possible to interpret the results as a TE-mode provided the boundary conditions are chosen properly. On the axis $r = 0$, the boundary condition is $H = 0$ (Dirichlet boundary) while the electric field is normal to the remaining boundaries (Neumann boundary). If one or both boundaries z = constant are symmetry planes, they can be either Dirichlet-type or Neumann-type depending on the field pattern of one's interest. For a given geometry, resonant frequencies are of course dependent on this choice of boundary conditions.

The original version of SUPERFISH was developed by R. F. Holsinger but the one which is presently available at Fermilab on the NOS system is the Los Alamos version with many convenient features added for interactive usage. One can use either a regular terminal or a Tektronix graphics terminal, the latter being more convenient for certain outputs.

Program Structure

The main part of SUPERFISH is made of four parts that must be executed in the following order:

1. FRONTX	(source program	FRONT)
2. AUTOX	("	AUTO)
3. LATTIX	("	LATTIC)
4. FISHX	("	FISH)

The first three are for preparing meshes and they all take a fraction of a second computing time. The last program, FISHX, is the main program and it may require several seconds of computing time for one evaluation of $D(k^2)$ when mesh points exceed $\sim$ 2,000. Certain parameters can be changed as input to FISHX without repeating three front programs. Once FISHX is finished, one can run several independent programs for various outputs of one's interest. These programs are

1. SF1X (source SFOUT1) For linac-type cavities, this gives stored energy, power dissipation, transit time factor and other quantities useful for beam dynamics, shunt impedance, maximum electric field on boundaries, and E_z on and near the axis r = 0. The program assumes that the geometry used in FISHX is one-half of the full cell.

2. SF2X (source SFOUT2) For a graphics terminal only. It gives a picture of horizontal mesh lines.

3. SF3X (source SFOUT3) This gives mesh coordinates (z, r) and magnetic field H_ϕ on the axis and on the first six rows.

4. SF4X (source SFOUT4) For a graphics terminal only. One can get a picture of either meshes or of field lines (rH_ϕ= constant which are electric field lines). The picture can be either the entire geometry or part of it enlarged depending on the input parameters XMIN, XMAX, YMIN, and YMAX.

5. SF6X (source SFOUT6)* Field lines plotted with numbers ranging from 0 to 9 and letters from A to J (negative values of rH). This is useful when one is using a regular terminal although SF4X is better with a graphics terminal.

6. SF7X (source SFOUT7) Field values on a specified line segment or a circular boundary or within a rectangular area.

Instructions

Sign on to the NOS system and do the following operations:

GET, FRONTX, AUTOX, LATTIX, FISHX, SF1X, ..., SF7X/UN=90965.

(Not all SF programs are needed for most cases.)

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* SF5 is not ready. SF8 is being developed at LASL.

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ATTACH, GRALIB/UN=NEWLIBR.
X, LIBRARY, GRALIB.
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These are recommended even when one is using a regular terminal. Otherwise, there will be an error message. One must then create a work file called DATA for data statements. Once this is done, the user executes FRONTX, AUTOX, LATTIX, and FISHX in this order. After FISHX is completed, any SF programs can be called for desired results.

How to prepare the file DATA

Each statement consists of a label followed by an ordered array of free-format numbers. Numbers must be separated by one or more blanks (or a comma). Decimal points in numbers are optional, for example both 5 and 5. are acceptable. The order of the numbers in a given statement is all-important but the order of the statements is generally unimportant except for obvious cases.

RUN n

where n = the run number for the user's convenience. This is the first card.

TITLE

indicates that the next statement is a title of up to 80 characters.

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title of up to 80 characters.

MESH h r_1 r_2

where h = the mesh dimension (horizontal and vertical) in cm. If r_1 is specified, the vertical mesh size is doubled at $r=r_1$. With r_2, the vertical mesh size is doubled again. The horizontal mesh size is always h. Although this feature is convenient for reducing the number of mesh points, the doubling should best be done when the cavity is "empty" beyond r_1 or r_2. If $r=r_1$ or r_2 lines cut boundaries other than the end walls (or the end symmetry planes), the accuracy is likely to be reduced. However, this may become unavoidable for some cases because of the maximum allowed mesh points.

Avoid doubling where r_1 and r_2 are too close to the endpoints of geometrical segments.

NSEG n

where n = the number of straight and circular line segments making up the boundary. This statement must precede the corresponding ZSEG, RSEG, and CSEG statements. Do not take circular arcs extending more than 90 degrees. Divide them into two or more segments.

ZSEG z_1 z_2 ..... z_n

z coordinates (in cm) of the endpoints of segments. It is assumed that the region is closed and that the endpoint of the last segment is the beginning point of the first segment. Go clockwise.

RSEG r_1 r_2 ..... r_n

r coordinates (in cm) of the endpoints.

CSEG c_1 c_2 ..... c_n

the radius of curvature (in cm) of each segment. A zero value indicates a straight line and a positive radius implies a circular arc that is convex looking from the inside of the region. See Fig. 1. If all c's are zero, this statement can be omitted.

In principle, one can specify multiple domains (see Fig. 1B) by repeating NSEG to CSEG statements.

MESHMAP

This causes AUTOX to produce a character-based mesh point map. Optional.

GRAPHICS s b

Graphics terminal only. The scale factor s specifies the size of the boundary picture produced by FRONTX. The value of s is limited by

$$512 + s\times(\text{horizontal cavity length}) < 1024,$$
$$40 + s\times(\text{vertical cavity size}) < 780$$

where (1024, 780) usually define the full size of the scope. The rate of the computer port is specified by b which can be 30, 120, 240 or 960 (or whatever). If the mesh size is doubled, there will be one or two horizontal lines indicating where the doubling is made. The scale factor s is only for FRONTX.

BOUNDARY t b r ℓ

where t, b, r, and ℓ are either 0 or 1 specifying the boundary conditions for the top, bottom, right, and left (outermost) borders of the geometry; 1 specifies a Neumann boundary (infinitely conducting wall, electric field normal to the boundary), 0 is for a Dirichlet boundary (H=0, electric field parallel). If this statement is omitted, the program assumes (1 0 1 1). In most cases, b = 0 and t = 1.

DRIVE n

where n = the segment number at the end of which the drive point is located. The default location is the uppermost point on the extreme left border of the problem. It is recommended to omitt this statement unless one is positive that the magnetic field is zero at the default location. The drive point should not be at the place where H=0. Important: See the note below for renumbering of segments when the mesh size is doubled.

FREQ f

where f = the value of the frequency (in MHz) for the first evaluation of $D(k^2)$. It is often better to omit this statement and to specify the initial frequency as an input to FISHX.

SCAN f_1 f_2 d

SUPERFISH will evaluate $D(k^2)$ at each frequency from f_1 to f_2 in steps of d (all in MHz). Again it is often better to do this as inputs to FISHX. The scanning is very useful when one wants to get an overall picture of the frequency spectrum.

POWER n_1 n_2 ......

where n's indicate the segment numbers over which the power losses and peak electric field calculations are made. Units are watts and MV/m respectively with the normalization of the average E_z on the axis = 1 MV/m. Important: See the note below for renumbering of segments when the mesh size is doubled.

BEGIN

marks the end of the data statements and the beginning of the execution.

END This should be the last statement of DATA.

Note : This applies to the statements DRIVE and POWER (and the output of AUTOX). It does NOT apply to the statements NSEG, ZSEG, RSEG, and CSEG.

When the doubling of the vertical mesh size is requested through the statement MESH (with r_1 and r_2), the numbering of segments is changed for DRIVE and POWER. See Fig. 2. NSEG, ZSEG, etc. in DATA are not affected by the doubling of mesh size.

There are three optional statements convenient for linac cavity.

DTLIN ℓ d g h r n b a

These eight numbers form a complete description of the common drift tube linac cell: ℓ = cell length, d = cell diameter, g = gap length, h = drift tube diameter, r = drift tube corner radius, n = drift tube nose corner radius, b = bore radius, a = face angle of drift tube. This eliminates the need for the use of NSEG, ZSEG, RSEG, and CSEG. See Fig. 3A.

SCLIN ℓ d g c r i n b t

These nine numbers form a complete description of the common coupled cavity linac cell for high-beta: ℓ = cell length, d = cell diameter, g = gap length, c = cone angle, r = outer corner radius, i = inner corner radius, n = nose corner radius, b = bore radius, t = septum thickness. See Fig. 3B. This is primarily intended to be for the LASL side-coupled cavity.

GAPCON z p

Again this is mostly for linac applications. z = the z coordinates of the center of the gap, p = the change in phase (degrees) of the rf during the transit of the synchronous particle across the portion of cavity described in the mesh. The default values for these are 0 and 180, which are the proper values for the half cell of drift tube linac cavity. For the π-mode standing wave cavity (high-beta), the appropriate values are 0 (cm) and 90 degrees. These values are used in the evaluation of the transit time factor and other quantities useful for beam dynamics and available from SF1X. When p is less than unity, it is interpreted to be the particle velocity/c. This option is convenient for buncher-type calculation.

Input Option of FISHX

When statements of DATA are changed, it is necessary to start again from FRONTX. The only exceptions to this are FREQ and SCAN. These can be modified when FISHX requests input. Often it is more convenient to omit FREQ or SCAN in the file DATA and specify them for FISHX. The input request from FISHX is

PROBCON INPUT (HIT CR FOR NONE) ?^*

If either FREQ or SCAN is in the file DATA and no change is desired, one responds with a carriage return. If the starting frequency is going to be, say, 450 MHz, the response is

*65 450 S (carriage return)

For SCAN, if the starting frequency is 350 MHz, the step size is 25 MHz and the total number of steps desired is 12 (the last frequency 625 MHz), the response should be

*65 350 *57 25 *54 12 S (carriage return)

For these changes, there is no need to run FRONTX, AUTOX, and LATTIX again.

Comments

SUPERFISH is never meant to perform a magic. For a successful run of the program, experience, patience and inteligence (not always in that order) on the part of the user are essential ingradients. Comments given below are simply suggestions based on my very limited experience and they are definitely not a cure-all recipe.

One weak point of SUPERFISH is that the function $D(k^2)$ takes negative values in a very limited range in frequency.[4] As a consequence, unless the initial value of frequency is close to the correct one, the frequency may converge to that of higher modes. After all, one evaluation of D cannot tell which way k^2 should go. It is always a good practice to make a quick scan of the frequency spectrum with a rather large mesh size. If D decreases and then starts increasing in some frequency region, it always goes through zero somewhere in-between. Once the frequency range of one's interest is established, the scan may be repeated with a smaller mesh size in a narrower range. The final run of FISHX should be made with the smallest possible mesh size. Here, the caution for the mesh doubling (p. 5, MESH) should be kept in mind. As it stands now, the maximum number of mesh points allowed is slightly less than 3,000. If the number exceeds the limit, AUTOX will give a message and the execution will be terminated.*) Whether a given size of mesh is small enough for the desired accuracy is a difficult question to answer. One can get a partial answer by plotting the converged values of frequency as a function of the mesh size, a time consuming process. According to Halbach, existence of many triangles with angles larger than 90° is an indication that the accuracy is not as good as otherwise. Enlarged mesh plottings which are available from SF4X are ideal for checking this.

SUPERFISH is still getting improved by Holsinger and by people at Los Alamos. There will be more SF type programs which may become available soon, for example the calculation of the stem perturbation on frequency and the power loss on stems.

Mike Harrison, Dave Johnson and members of the Computing Department kindly helped me in making the program available at Fermilab.

References

1. T. Edwards, MESSYMESH, MURA Report 622 (1961); Höyt, Simmonds, and Rich, Rev. Sci. Inst., 36 (1966), 755.
2. D. E. Johnson and S. Ohnuma, FN-299, September 1976.
3. K. Halbach is planning to include the case in which ϕ-dependent fields can also exist. However, the geometry will still be cylindrically symmetric.
4. Halbach feels that it should be possible to find a function which behaves better in this respect than $D(k^2)$.

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* If more mesh points are required, one must modify the source programs. See Appendix I.

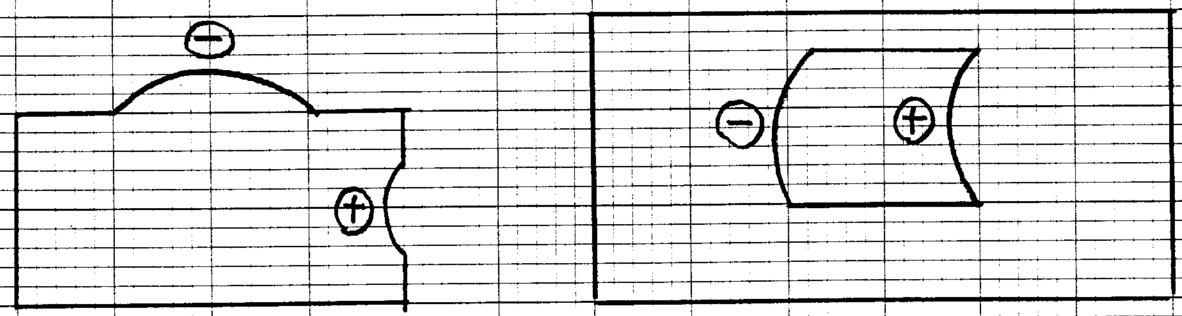

Fig. 1A

Fig. 1B

Sign convention of the radius of curvature.

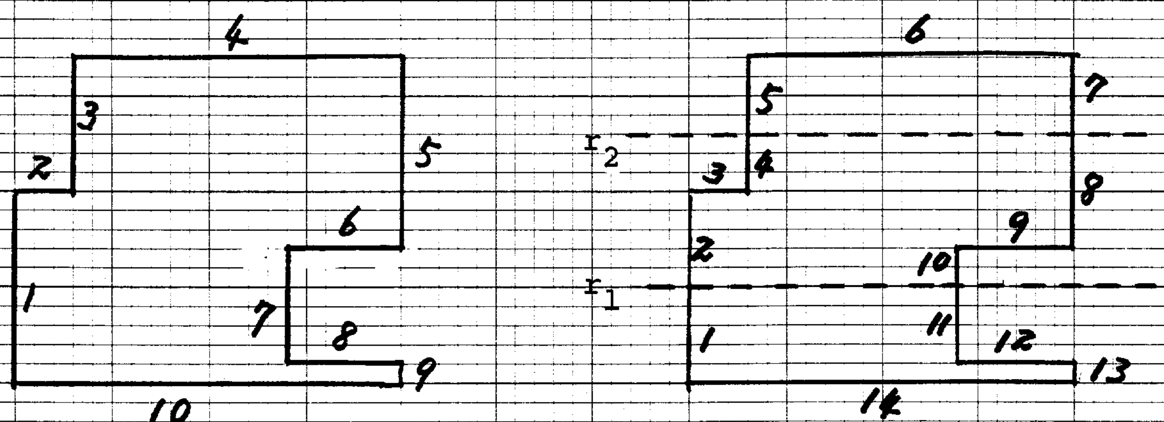

Fig. 2A

NSEG = 10

Fig. 2B

Segment numbering for DRIVE and POWER when the vertical mesh size is doubled.

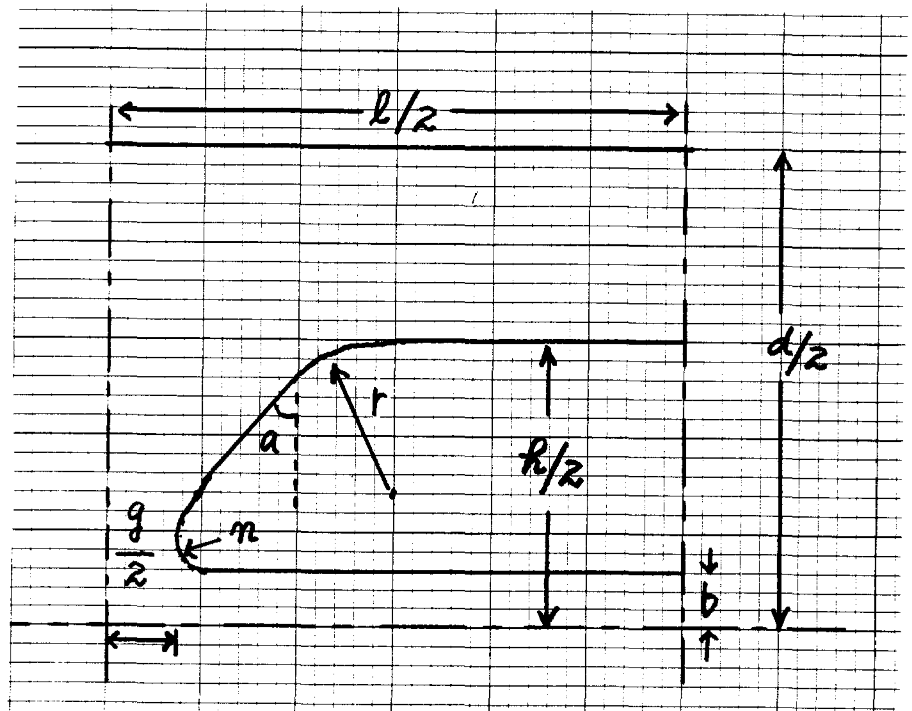

Fig. 3A. DTLIN ℓ d g h r n b a

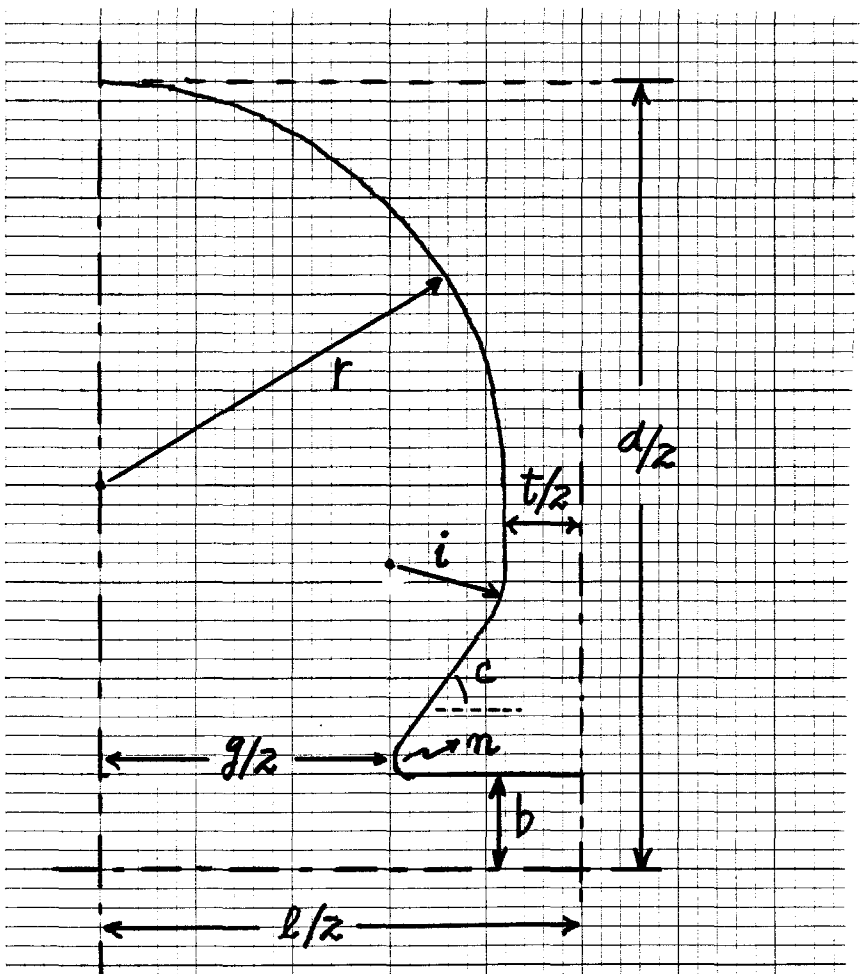

Fig. 3B

SCLIN ℓ d g c r i n b t

Appendix I. How to Increase the Maximum Allowed Number of Mesh Points.

In the following, editing with ICE is assumed.

1.	FRONT	No change required.
2.	AUTO	FW/3000/W Change all 3000 to, say, 4000. Four places.
3.	LATTIC	FW/3000/W Change all 3000 to 4000. Five places.
4.	FISH	FW/3000/W Change all 3000 to 4000. Twelve places. FW/6000/W Change all 6000 to 8000. Three places.
5.	SFOUT1	Change 3000 to 4000. Four places.
6.	SFOUT2	Change 3000 to 4000. Four places.
7.	SFOUT3	Change 3000 to 4000. Four places.
8.	SFOUT4	Change 3000 to 4000. Four places.
9.	SFOUT6	Change 3000 to 4000. Five places.
10.	SFOUT7	Change 3000 to 4000. Five places.

Appendix II. Example.

Figs. 4A-E are examples of some outputs one gets on a graphics terminal. The geometry is shown in Fig. 4.

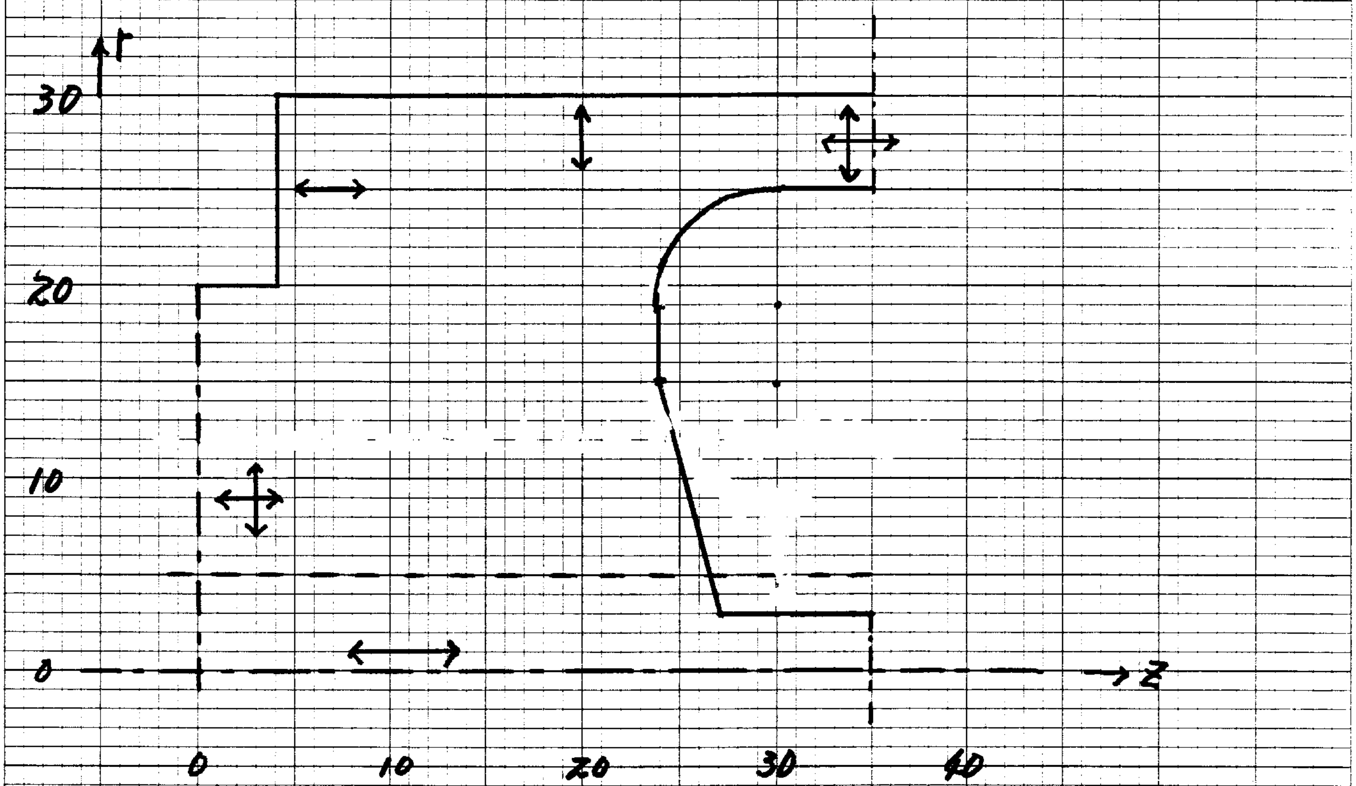

Fig. 4. Geometry of the example; one-half cell.

```
SUPERFISH PROGRAM            17.54    79/09/21          RUN  500

DEMONSTRATION

RUN 500
TITLE
DEMONSTRATION
MESH 1 5
NSEG 12
ZSEG 0 4 4 35 35 30 24 24 27 35 35 0
RSEG 20 20 30 30 25 25 19 15 3 3 0 0
CSEG 0 0 0 0 0 0 6 0 0 0 0 0
GRAPHICS 12 120
BOUNDARY 1 0 0 1
POWER 3 4 5 7 8 9 10 11 12
BEGIN

    .074 CP SECONDS EXECUTION TIME
```

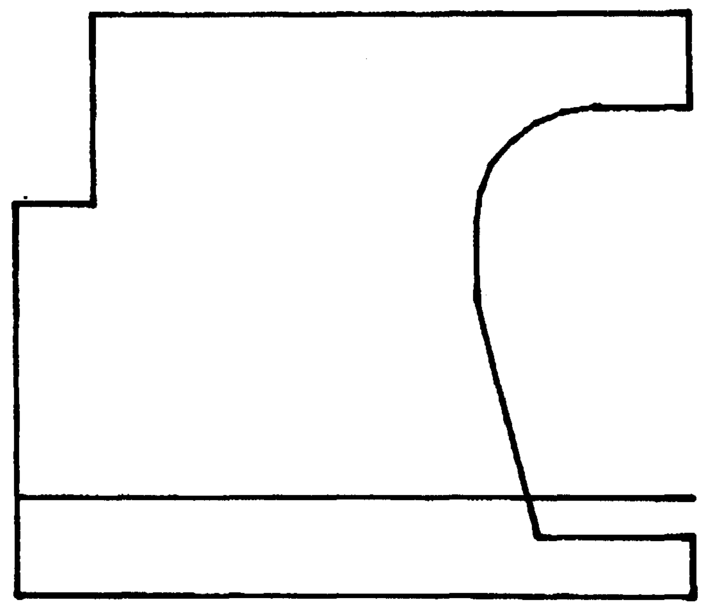

Fig. 4A. Output of FRONTX on a graphics terminal.

1

```
SUPERFISH (FROM TAPE37)
DEMONSTRAT
FROBCON INPUT (HIT CR FOR NONE) ?^*
? *65 595 *54 15 *57 1 S

ELAPSED TIME  -  CPU = 47.447

CYCLE    HMIN          HMAX        RESIDUAL
   0   0.            0.           1.0000E+00
----------------------------------------------------------------
                       K**2 =  1.5551E-02   FREQ =  5.9500E+02

STEP FREQ WITH DRIVING POINT AT K =  1 L = 16
```

N	FREQ	K**2	DELTA	D
1	595.000	.015551	.400650	.000706
2	596.000	.015603	.290780	.000335
3	597.000	.015655	.112410	.000075
4	598.000	.015708	-.227671	-.000072
5	599.000	.015761	-1.132138	-.000108
6	600.000	.015813	-10.869842	-.000030
7	601.000	.015866	3.882265	.000161
8	602.000	.015919	2.199533	.000467
9	603.000	.015972	1.720724	.000887

Fig. 4B. FISHX in SCAN mode.

SUPERFISH OUTPUT (SF04) 10.37 79/09/20

RUN NO. 500 TITLE = DEMONSTRAT FREQUENCY = 0.000

XMIN, XMAX, YMIN, YMAX = 22.000 32.000 17.000 27.000

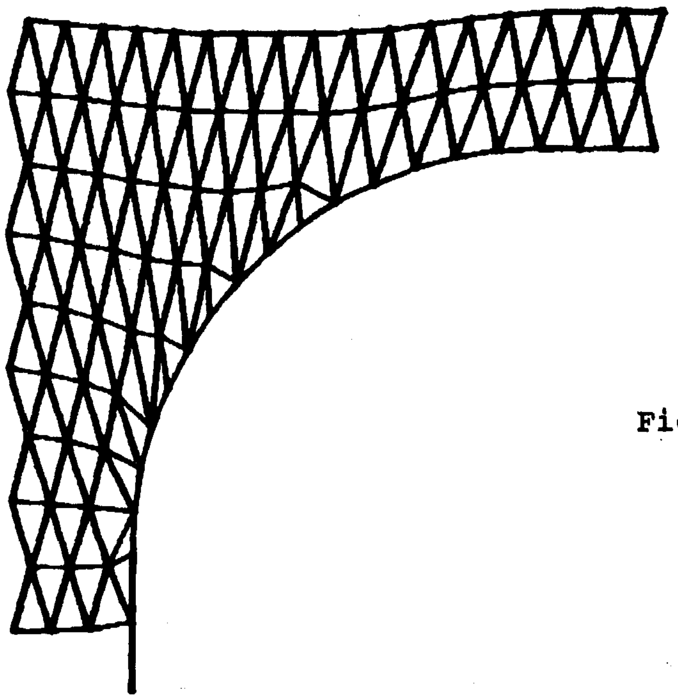

Fig. 4C. Enlarged mesh map from SF4X.
Some triangles have angles larger than 90°.

SUPERFISH OUTPUT (SF04) 10.52 79/09/20

RUN NO. 500 TITLE = DEMONSTRAT FREQUENCY = 790.281

XMIN,XMAX,YMIN,YMAX = 0.000 35.000 0.000 30.000

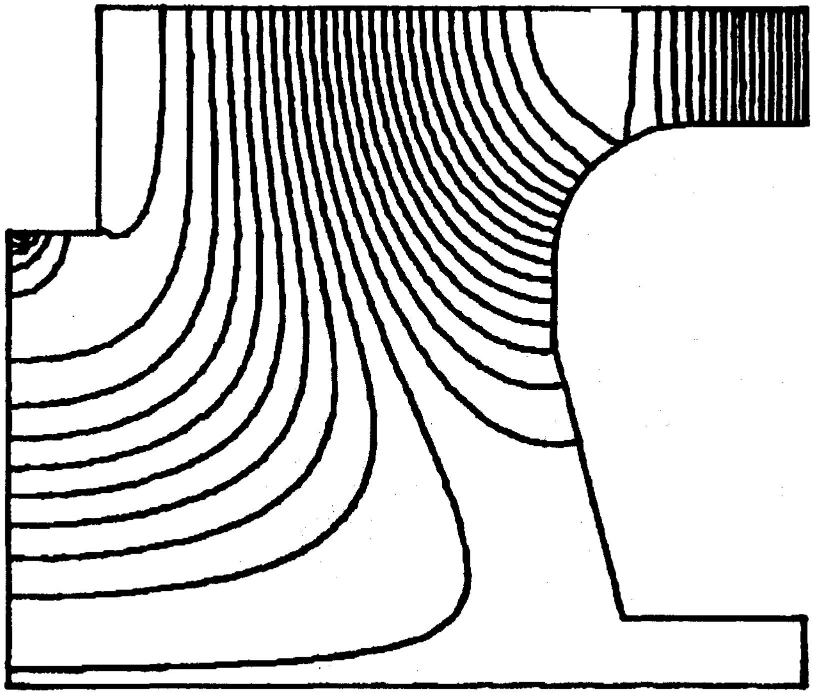

Fig. 4D. Map of Field Lines from SF4X.

```
...................................................
......898888888888888888888877777666655443322 1100.
.......8888888888888888888888777777666655443321100.
......88888888888888888877777777766666655433221100.
.......7777777777777777777777776666666.............
.4455556666666666666666666666666655................
.4444445555555555555555555555555554................
.3333344444444444444444444444444443................
.22223333333333333333333333333333333...............
.*22222222222222222222222222222222221..............
.1111111111111111111111111111111111111.............
.1111111111111111111111111111111111100.............
.0000000000000000000000000000000000000.............
.0000000000000000000000000000000000000.............
.00000000000000000000000000000000000000............
.00000000000000000000000000000000000000............
.0000000000000000000000000000000000000000000000000.
.0000000000000000000000000000000000000000000000000.
.000000000000000000000000000000000000000P000000000.
.0000000000000000000000000000000000000000000000000.
.0000000000000000000000000000000000000000000000000.
.0000000000000000000000000000000000000000000000000.

...................................................

RH ARRAY VALUES RANGE FROM   0.00000 TO   45.20536
* MARKS THE DRIVE POINT
     .044 CP SECONDS EXECUTION TIME
```

Fig. 4E. Character-based Field Lines from SF6X, Regular or Graphics Terminal.