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"Calibration Procedures and Data Reduction Techniques for Transonic Aerodynamic Probes"

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Abstract

A description is given of the procedures employed at the Energetics Department of Genoa University to calibrate aerodynamic probes for variations in Mach number and pitch angle, putting into evidence the difficulties arising in particular during the operation in the transonic range. The problem of the automatic data reduction is also considered and a simple technique is developed, suitable for the application on minicomputer, that allows to deduce the actual values of Mach number and flow angle of the cascade under investigation from the measured probe pressure values, without the need for iteration. This is done through the introduction of non dimensional probe coefficients whose correspondence with the actual flow parameters is numerically and graphically analyzed. Some results obtained by means of the proposed method are compared with those given by the more traditional iterative approach.

1. Introduction

The experimental investigation on the performances of two-dimensional cascades, oriented toward the assessment of both cascade flow properties and losses at nominal and off design conditions, requires the careful survey of the cascade exit region by means of aerodynamic probes, whose calibration characteristics have to be known with a high degree of accuracy. The choice of the probes and of their calibration procedures depends largely on the flow parameters and flow regime to be investigated. In case of plane turbine or compressor cascades, the downstream distribution of the flow Mach number, angle and total pressure can be obtained by means of a single combined two-dimensional probe. Two different probes of this kind, suitable for the operation in a wide range of Mach numbers (from Ma $\simeq$ .5 up to Ma $\simeq$ 2.) have been manufactured at the Energetics Department of Genoa University. For a description of the probes and of the technological procedures involved in their construction, the reader is referred to [1], where the authors give also a complete presentation of the variable geometry transonic tunnel used for probe calibration and of the methods employed to minimize the blockage effect.

In the present paper, which can be regarded as complementary to the one cited above, the problem of the correct interpretation of the probe readings obtained during downstream cascade traverses, is taken into consideration. To this aim it is required, on the one hand, to evaluate the probe response during its calibration in a flow of known characteristics, and, on the other hand, to set up a data reduction procedure suitable to reach the correct values of the flow under investigation from the probe readings.

In the paper, after a brief description of the adopted instrumentation, especially as far as data acquisition and elaboration techniques are concerned, the data reduction problem is considered in detail and a newly developed non iterative method is presented, that, in authors' opinion, can offer some advantage when compared with other existing approaches.

2. Instrumentation

The apparatus used to calibrate the probe is schematically shown in fig. 1, together with the instrumentation adopted to obtain an automatic data acquisition and data elaboration for the five pressure values measured during the calibration :

p_s, p_t, $(p_{left} - p_{right})$ (probe pressure readings)

$p_{s,ref}$, $p_{t,ref}$ (tunnel pressure readings)

All pressures are converted to voltages by calibrated Schaewitz transducers of different measuring range, for which the reference pressure is atmospheric.

The data acquisition system consists of the input/output device which performs sampling, multiplexing and analog/digital conversions, and the computer, which is used both to control the acquisition unit and to perform the data processing. The processed data can then be stored or displayed in graphical or numerical form and finally sent to the computer peripherals (printer and plotter). The system is based on the HP 3497A data acquisition/control unit, whose main features are its 60 multiplexer channels capability, its 16 digital inputs and 16 actuator outputs, a 5½ digit, 1 microvolt sensitive DC voltmeter, a measurement speed of 300 readings per second.

The control unit is the HP model 9816 computer, which has a 9 inch monochrome CRT display, a detached keyboard, a 512 KB memory and two floppy disks. The controller is interconnected with the data acquisition unit and with the peripherals by means of the HP-IB interface bus, as sketched in the scheme.

The tunnel instrumentation comprises also two multimanometers connected with the matrix of 9x9 static tappings described in [1], located on the perspex window in correspondence of the probe head, and a flow visualization apparatus, a single pass schlieren system of the Toepler type, already discussed in [1,2], which allows to perform both black and white and coloured schlieren visualizations and is equipped with videocamera and monitor enabling a continuous inspection and control of the test section during probe calibration.

3. Probe Calibration

The calibration of a combined probe, such as those presented and discussed in [1,3] (a needle static probe and a wedge probe), by means of the variable geometry transonic tunnel of Genoa University, requires the following sequence of operations:

- imposition of the nozzle geometry corresponding to the desired Mach number by regulating the screw jacks of the flexible walls with the help of the jigs described in [1];
- insertion and alignement of the probe in the test section;
- after the tunnel is started, verification of the flow situation in the test section by means both of the optical system and of the multimanometer connected to the 9x9 static tappings;
- relief of the blockage effect, if present, by locally operating on the nozzle walls as explained in [1];
- step by step variation of the pitch angle by means of the suitable rotating rim linked to the probe holder;
- acquisition, for every pitch angle, of the five pressure values indicated in the scheme of fig. 1.

The above operations have to be repeated for each calibration Mach number. When all the pitch angles and Mach numbers have been experimented, a simple elaboration procedure allows to represent the following non dimensional coefficients :

$$K_{pt} = \frac{p_{t,ref} - p_{t,probe}}{(p_t - p_s)_{ref}}$$ total pressure coefficient

$$K_{ps} = \frac{p_{s,ref} - p_{s,probe}}{(p_t - p_s)_{ref}}$$ static pressure coefficient

$$K_{\gamma} = \frac{(p_{left} - p_{right})_{probe}}{(p_t - p_s)_{ref}}$$ directional coefficient

computed for every tested situation, both in a two-dimensional and in a three-dimensional graphical form.

For the needle-static probe, the calibration curves for K_{pt}, K_{ps}, K_{γ} are reported respectively in fig. 2,3,4. The figs. 5, 6, 7 show the same coefficients plotted as three dimensional surfaces in a spatial reference frame.

During the calibration, a continuous inspection of the flow situation around the probe by means of the optical visualization system has contributed to reach confidence with this type of tests increasing the reliability of the results. As an example, figs. 8, 9 show photo visualizations of the flow field around respectively the needle probe and the wedge probe. The first picture shows the small disturbances due to the needle probe head and the presence, in this particular situation, of a channel normal shock wave in the test section, the second picture evidentiates the typical disturbances generated by the wedge probe in supersonic flow.

4. Data Reduction Procedures

As far as the data reduction problem is concerned, two different methods have been developed at the Energetics Department, University of Genoa. In both cases a calculation procedure is defined, based on a manipulation of the calibration data toward their utilization during automatic traverse data interpretation.

The first procedure, represented in block diagram form in fig. 10, is based on the traditional iterative approach usually employed for data reduction in transonic range. It can be summarized in the following main points :

1 - choice of tentative values for the reference total and static pressures;
2 - calculation of the correspondent tentative value for the Mach number;
3 - calculation of the flow angle by interpolation from the directional coefficient calibration map;
4 - interpolation from the total and static pressure coefficient calibration maps;
5 - calculation of corrected values for the total and static pressure;
6 - iteration up to convergence.

The major inconvenience of this indirect procedure, although widely and successfully used, is the difficulty, in some situations, especially near Mach = 1., to reach the convergence. For this reason, a new direct method has been developed, suitable also for application on mini computer, that is able to produce the actual values of Mach number and flow angle of the tested cascade by means of a solution algorithm applied to the probe pressure readings, without the need for iteration.

The procedure follows the points listed below.

1 - Manipolation of the calibration maps of K_{pt}, K_{ps}, K_{γ} in order to get a thicker distribution of the calibration coefficients. This is done by means of a two-dimensional interpolation subroutine that utilizes bicubic spline

interpolation to approximate the function values at the non-mesh points. In this way new calibration maps with finer grid are obtained.

2 - Introduction of alternative non-dimensional coefficients depending only on the probe pressure readings :

a) $$\beta = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{1}{X}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

$$\text{for } X = \frac{p_{s,probe}}{p_{t,probe}} > .528$$

$$\beta = A1 + X^* (A2 + X^* (A3 + X^* (A4 + X^* (A5 + X^* (A6 + X^* (A7 + X^* (A8 + X^* (A9 + X^* (A10 + + X)))))))))$$

$$\text{for } X = \frac{p_{s,probe}}{p_{t,probe}} < .528$$

where A1, A2,....A10 are constants determined through the inversion of the Rayley formula :

$$\frac{1}{X} = \left[\frac{(\gamma+1)^2\beta^2}{4\gamma\beta^2 - 2(\gamma-1)}\right]^{\frac{\gamma}{\gamma-1}} . \frac{1-\gamma+2\gamma\beta^2}{\gamma+1}$$

b) $$\delta = \frac{(p_{left} - p_{right})_{probe}}{p_{t,probe} - p_{s,probe}}$$

c) $$\xi = \frac{p_{t,probe}}{p_{t,ref}}$$

3 - The introduced coefficients β, δ, ξ are calculated for each mesh point of the calibration maps. It can be argued from their definition and it can be seen in the results that β is sensitive to the Mach number, δ to the pitch angle, and ξ to the total pressure. The figs. 11, 12, 13 show the variations of β, δ, ξ with the flow angle, taking the Mach number as parameter. In fig.14 a three dimensional representation of the Mach number surface in function of β and δ is presented. The same representation for the flow angle surface is shown in fig.15.

4 - Representation of the iso-Mach lines and of the iso-angle lines in the plane β, δ. As can be seen from fig. 16, the iso-Mach and iso-angle lines cross each other to

form a quadrilateral grid.

5 - Search of the quadrilateral mesh containing the input values β^*, δ^* corresponding to the probe pressure readings obtained during cascade traverses. This is done by means of a fast logical subroutine, which computes the area sign for the triangles formed among the considered point and the vertices of the quadrilateral meshes.

6 - Calculation of the Mach number and flow angle with the least squared method applied to the vertices of the quadrilateral mesh containing β^*, δ^*.

7 - Calculation of $p_{t,ref}$ from the previously determined calibration map of ξ in function of Mach number and flow angle.

In the outlined procedure, among the points listed above, the point 3, relative to the graphical representation of the correspondences between the introduced non dimensional probe coefficients and the actual flow parameters, can be obviously by-passed in normal applications, so allowing a further reduction of the computer time. Nevertheless the advantage of this new direct method of data reduction, as compared with the iterative one, rather than to the shorter time required, is due to its ability to attain the solution without problems of convergence. This is shown, although for a limited number of cases, in fig. 17, where the values of Mach number and flow angle obtained by using the new direct technique are compared with those given by the iterative procedure in correspondence of 6 different flow situations. In the figure, the dotted lines evidentiate the intervals of non convergence for the iterative procedure in three flow situations, whilst in all the examined cases the solutions are univocally determined by the new direct procedure.

5 - Conclusions

The discussion carried out allows some conclusions to be drawn :

- the variable geometry transonic tunnel of the Genoa University and the correlated instrumentation are suitable to perform semi automatic probe calibration with a high degree of reliability;
- the calibration procedures adopted for combined cascade exit survey probes are to be considered satisfactory in the whole range of Mach numbers of interest, including the transonic range;
- the newly developed, non iterative data reduction procedure presented in the paper has the advantage, if compared with other methods, to give the desired cascade flow values both by reducing the computer time and by avoiding problems of convergence.

REFERENCES

[1]- Pittaluga,F. ; Benvenuto,G. : A Variable Geometry Transonic Facility for Aerodynamic Probe Calibration, VIII Symposium on Measuring Techniques for Transonic and Supersonic Flow in Cascades and Turbomachines, Genoa, Italy, 24 - 25 October, 1985.

[2]- Benvenuto,G. ; Pittaluga,F. : Experimental Investigation on the Performances of a Transonic Turbine Blade Cascade for Varying Incidence Angles, XV ICHMT Symposium on Heat and Mass Transfer Measurement Techniques, Dubrovnik, Jugoslavia, September 1983.

[3]- Benvenuto,G. ; Pittaluga,F. : Metodologie di taratura di sonde miniaturizzate per rilievi del flusso in schiere di pale transoniche, XL A.T.I. Congress, Trieste, September 1985.

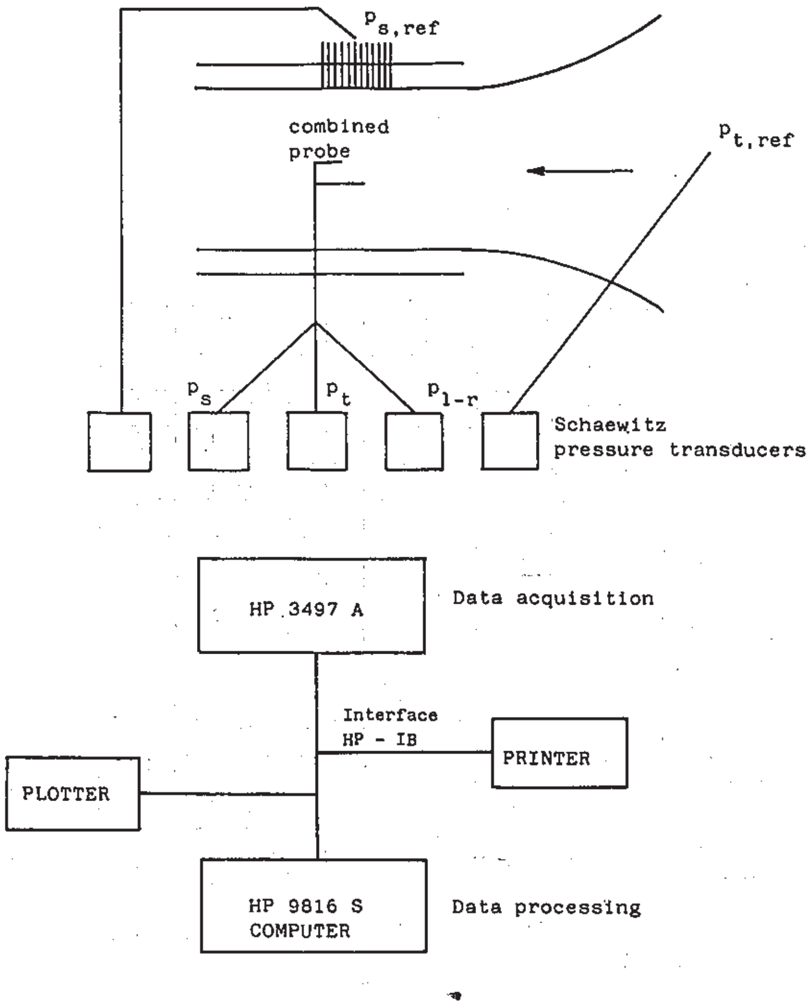
p_s,ref
combined probe
p_t,ref
p_s
p_t
p_l-r
Schaewitz pressure transducers
HP 3497 A
Data acquisition
Interface HP - IB
PRINTER
PLOTTER
HP 9816 S COMPUTER
Data processing

FIG. 1

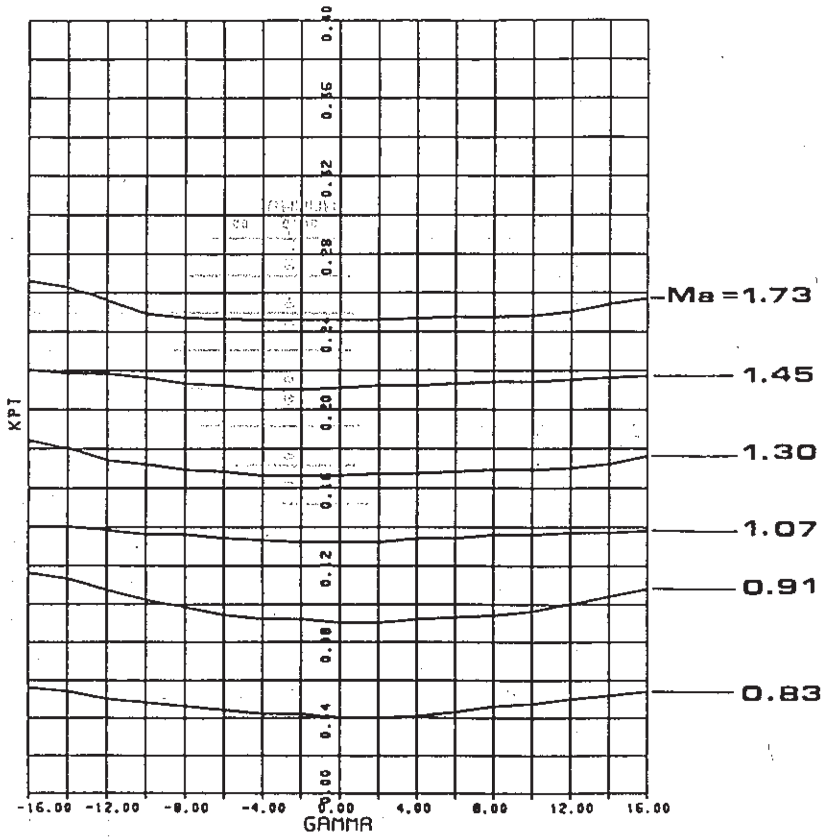
KPI
0.00
0.04
0.08
0.12
0.16
0.20
0.24
0.28
0.32
0.36
0.40
GAMMA
-16.00
-12.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00
Ma =1.73
1.45
1.30
1.07
0.91
0.83

FIG. 2

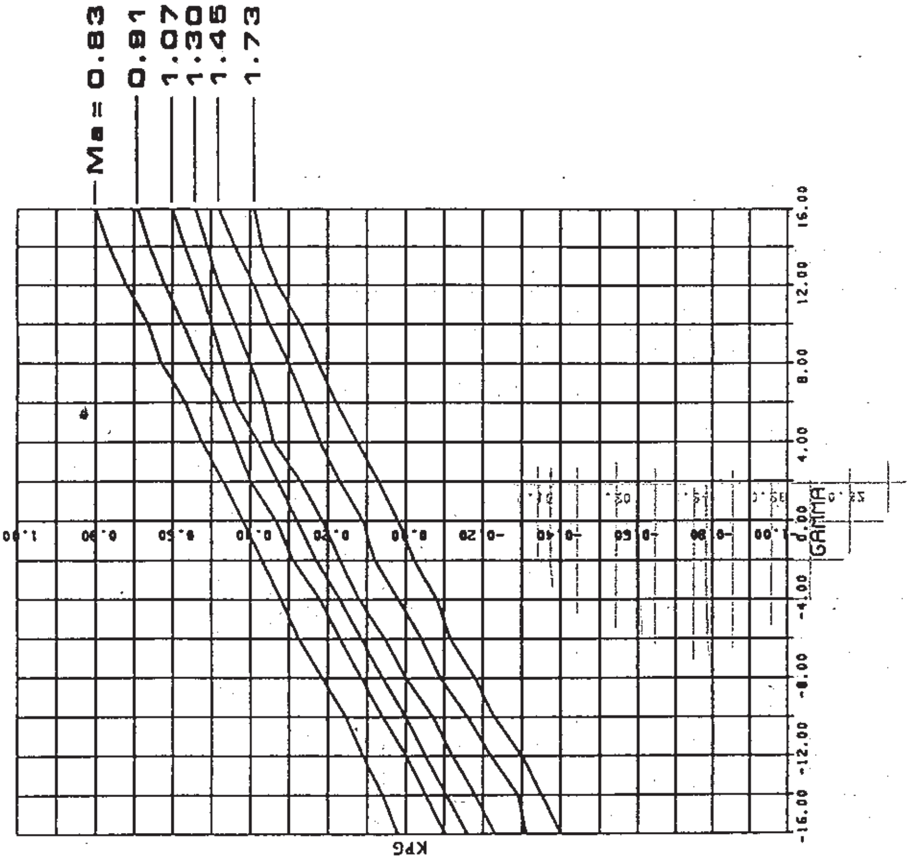
Ma = 0.83
0.91
1.07
1.30
1.45
1.73
KPG
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
GAMMA
-16.00
-12.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00

FIG. 4

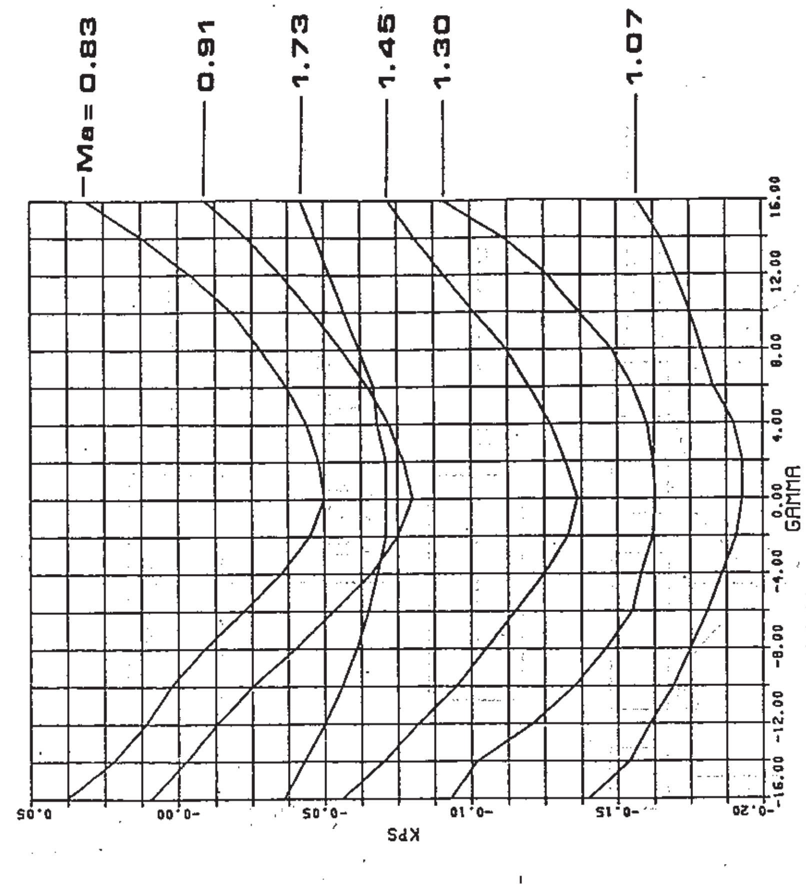
Ma = 0.83
0.91
1.73
1.45
1.30
1.07
KPS
0.05
0.00
-0.05
-0.10
-0.15
-0.20
GAMMA
-16.00
-12.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00

FIG. 3

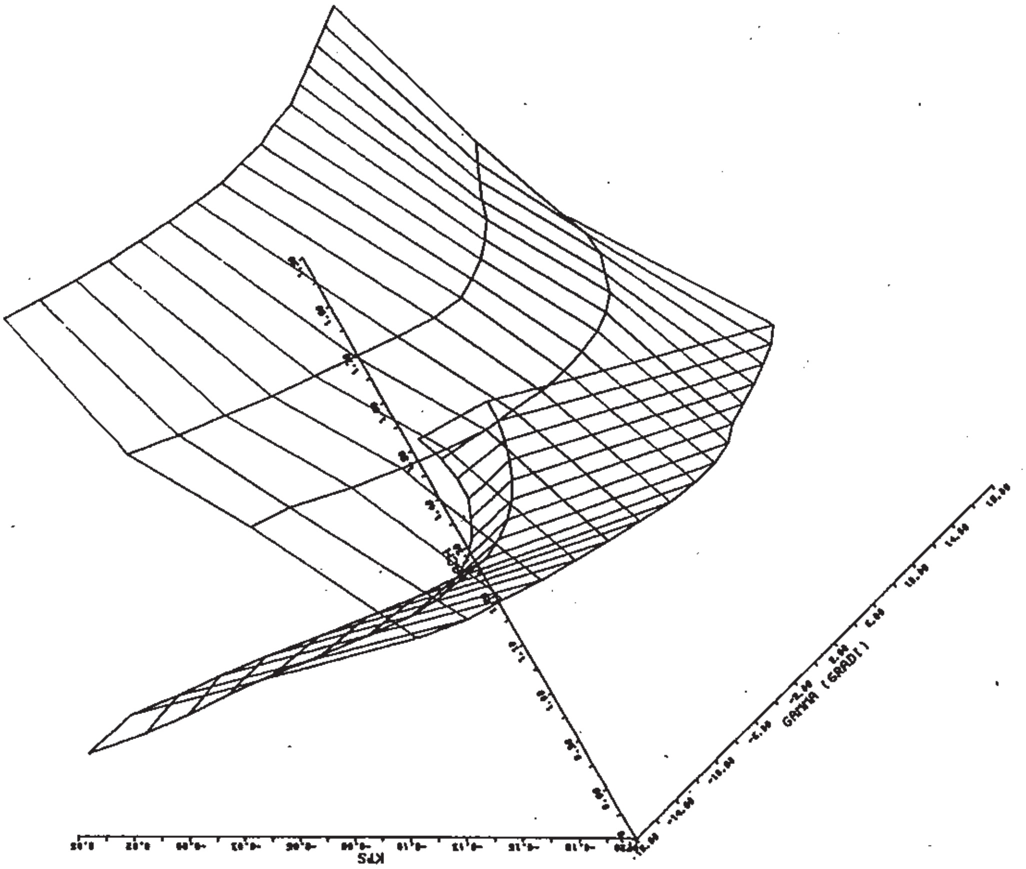

FIG. 6

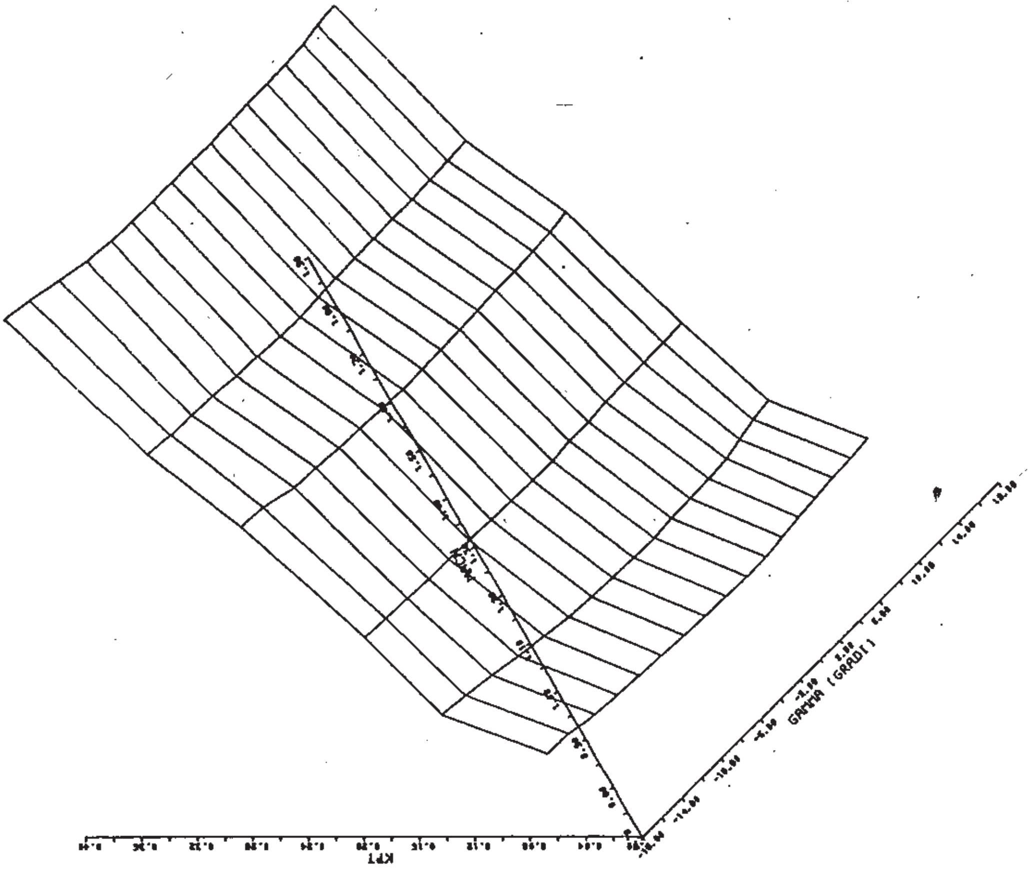

FIG. 5

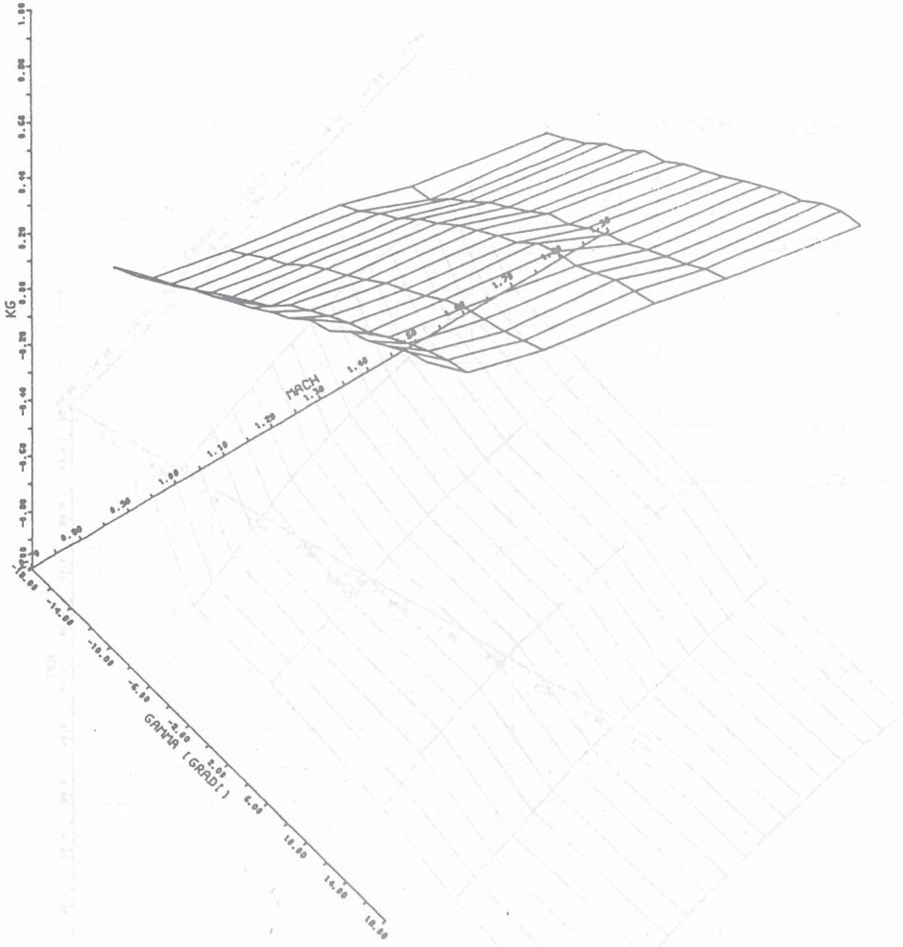
KG
-1.00
-0.80
-0.60
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
MACH
0.80
0.90
1.00
1.10
1.20
1.30
1.40
GAMMA (GRADI)
-18.00
-14.00
-10.00
-6.00
-2.00
2.00
6.00
10.00
14.00
18.00

FIG. 7

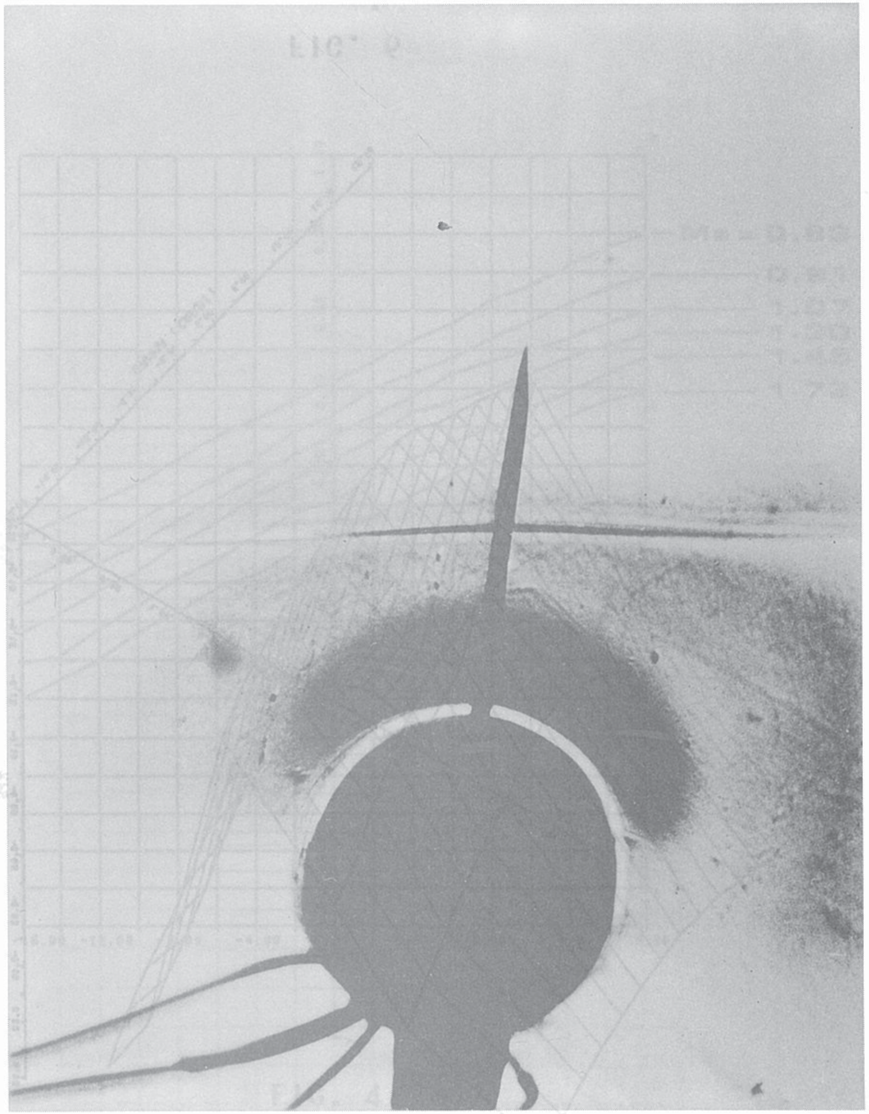

FIG.8

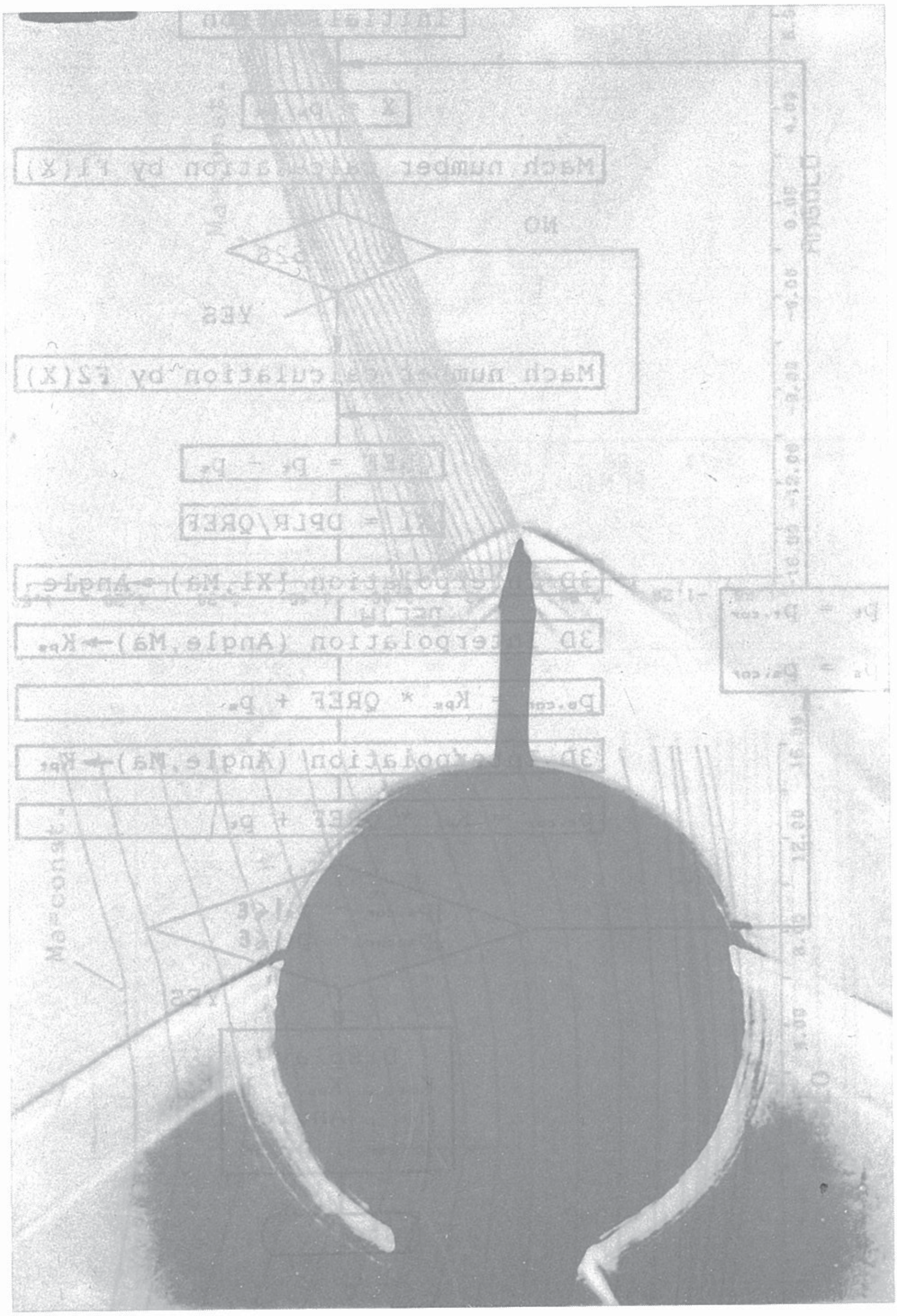

FIG. 9

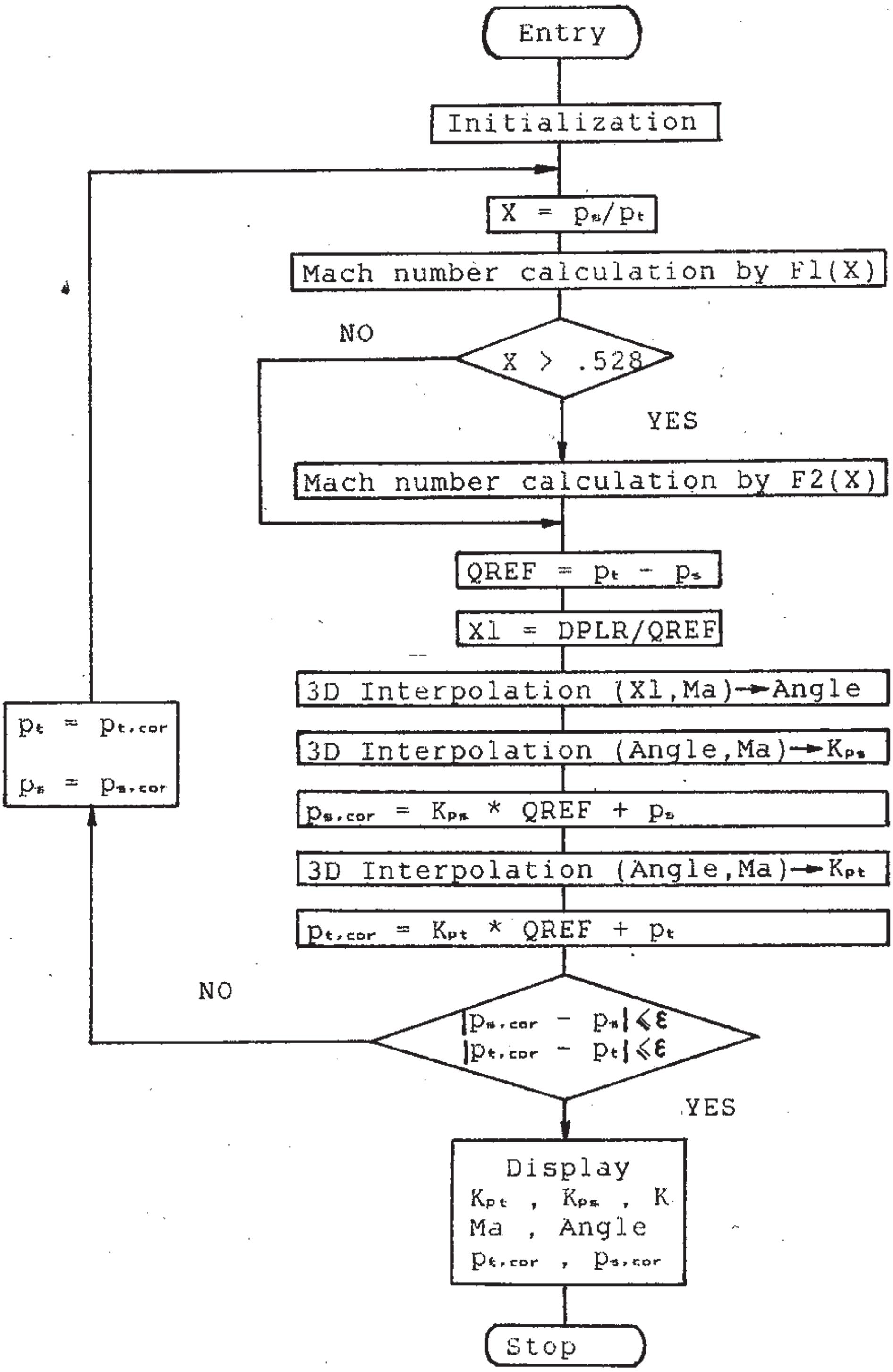
Entry
Initialization
X = p_s/p_t
Mach number calculation by F1(X)
NO
X > .528
YES
Mach number calculation by F2(X)
QREF = p_t - p_s
X1 = DPLR/QREF
3D Interpolation (X1,Ma)→Angle
3D Interpolation (Angle,Ma)→K_ps
p_s,cor = K_ps * QREF + p_s
3D Interpolation (Angle,Ma)→K_pt
p_t,cor = K_pt * QREF + p_t
p_t = p_t,cor
p_s = p_s,cor
NO
|p_s,cor - p_s| ≤ ε
|p_t,cor - p_t| ≤ ε
YES
Display
K_pt , K_ps , K
Ma , Angle
p_t,cor , p_s,cor
Stop

FIG. 10

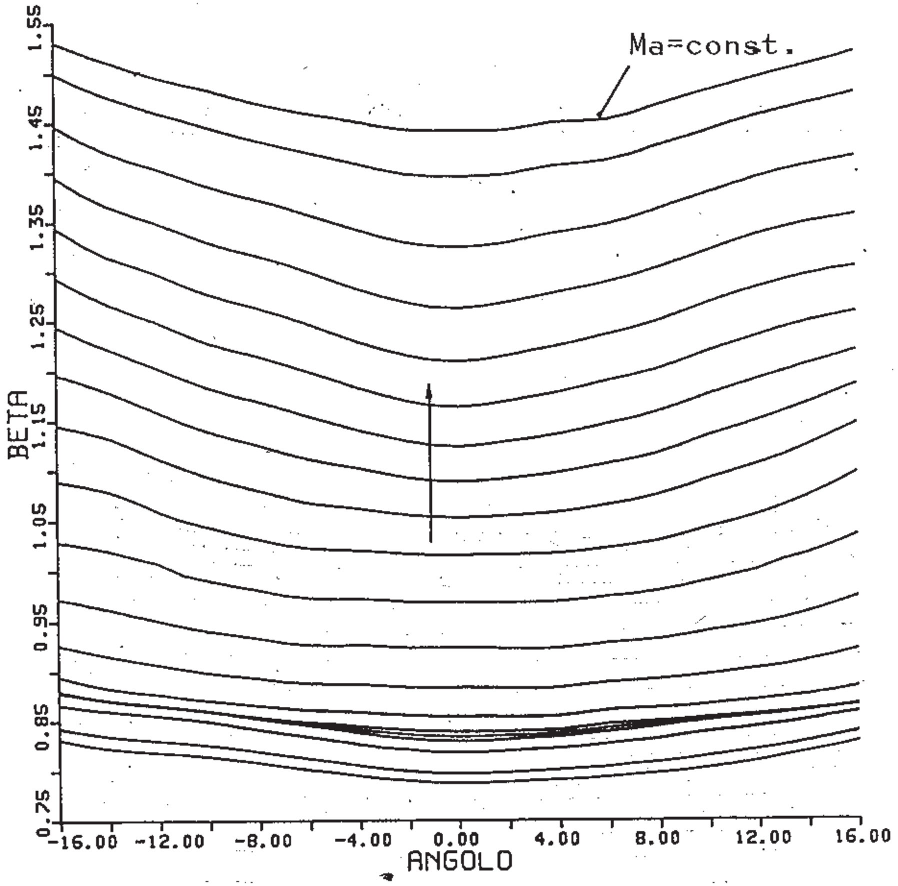
Ma=const.
BETA
1.55
1.45
1.35
1.25
1.15
1.05
0.95
0.85
0.75
-16.00
-12.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00
ANGOLO

FIG. 11

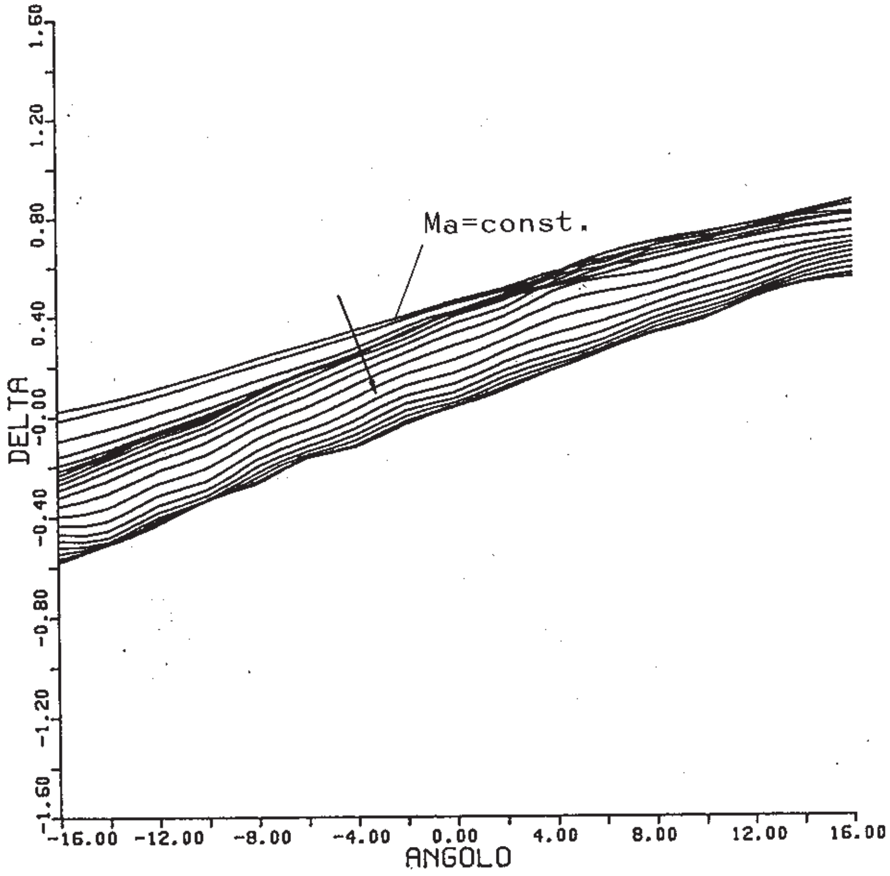
Ma=const.
DELTA
1.60
1.20
0.80
0.40
-0.00
-0.40
-0.80
-1.20
-1.60
-16.00
-12.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00
ANGOLO

FIG. 12

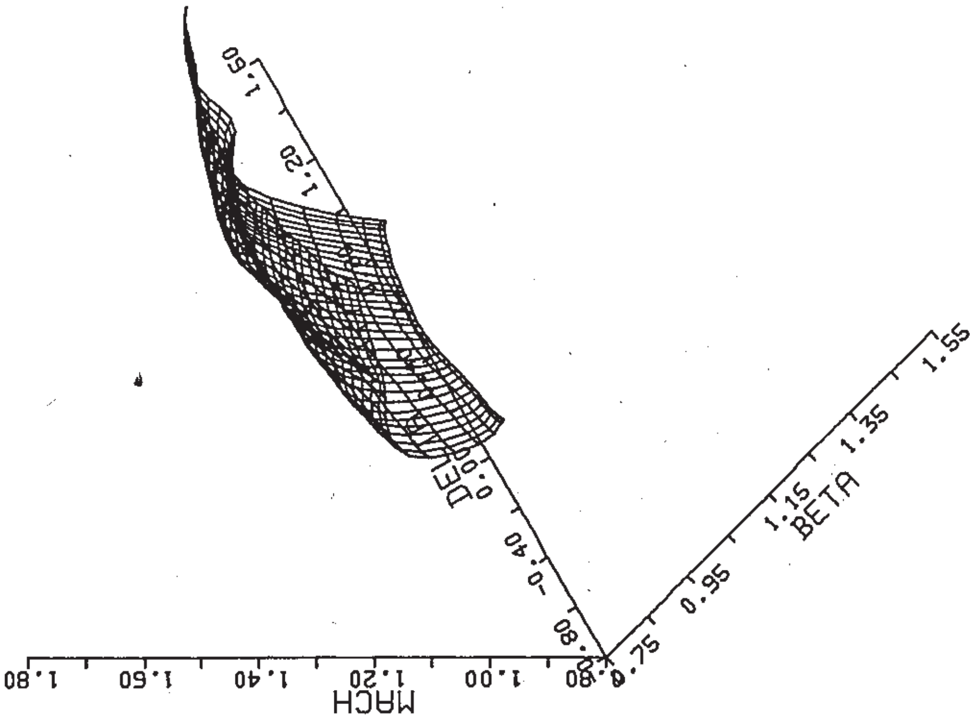
MACH
0.80
1.00
1.20
1.40
1.60
1.80
DE
-0.80
-0.40
0.00
1.20
1.60
BETA
0.75
0.95
1.15
1.35
1.55

FIG. 14

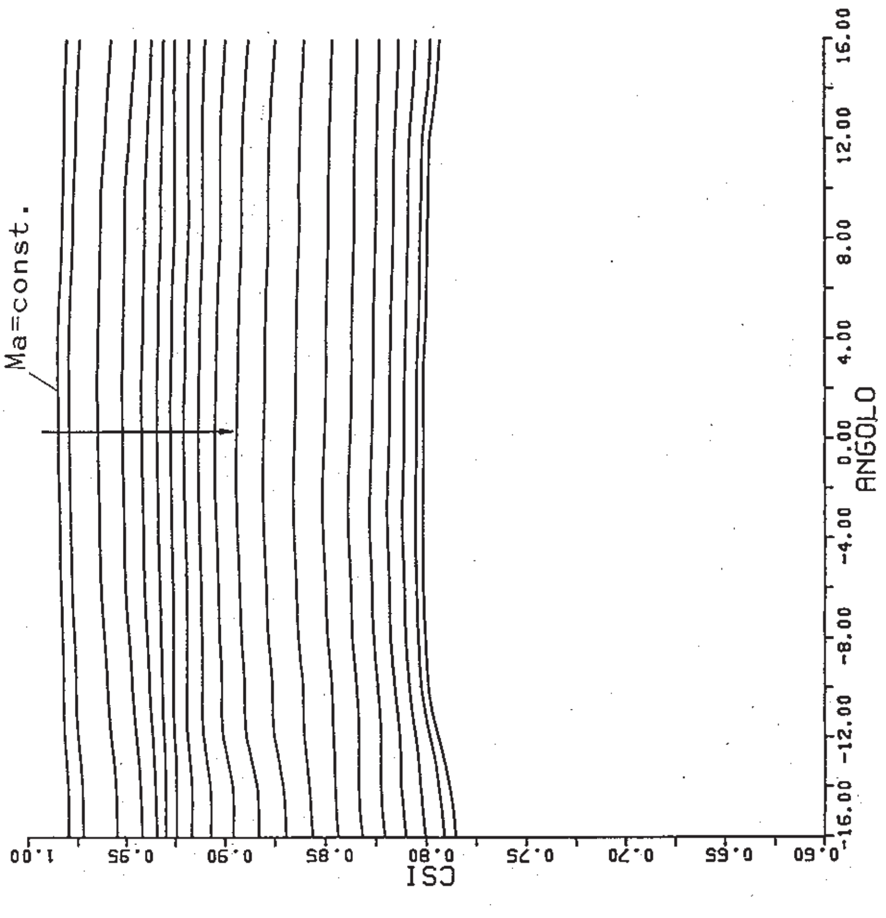
Ma=const.
CSI
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
ANGOLO
-16.00
-12.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00

FIG. 13

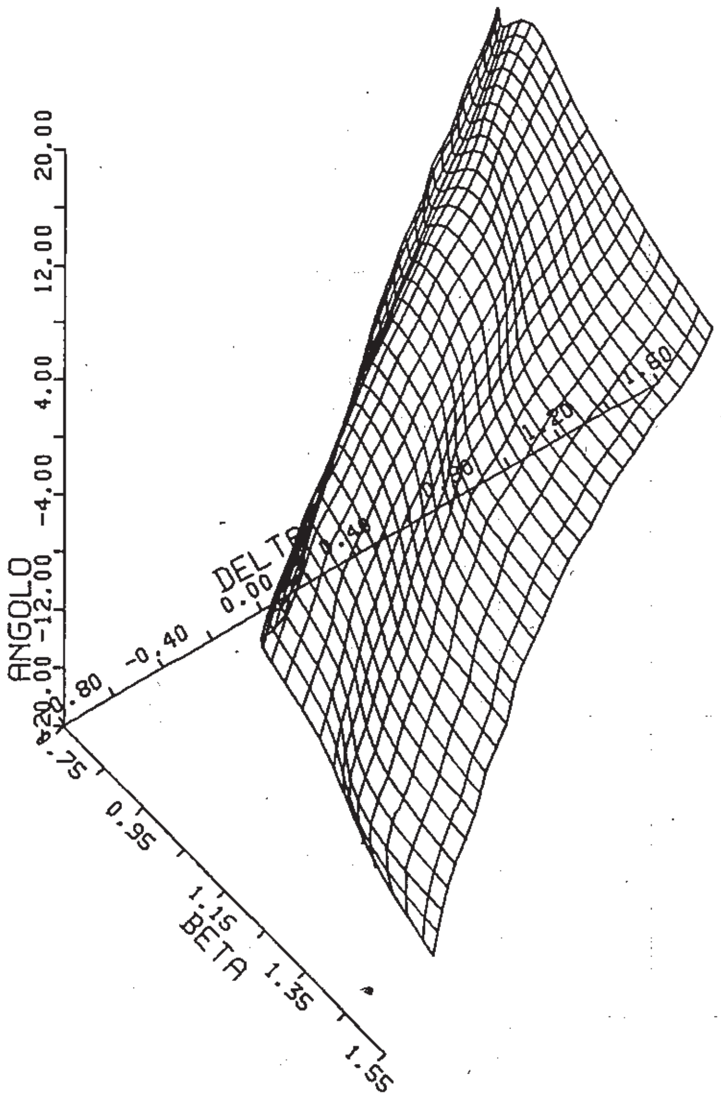
ANGOLO
20.00
12.00
4.00
-4.00
-12.00
-20.00
DELTA
-0.80
-0.40
0.00
0.40
0.80
1.20
1.60
BETA
0.75
0.95
1.15
1.35
1.55

FIG. 15

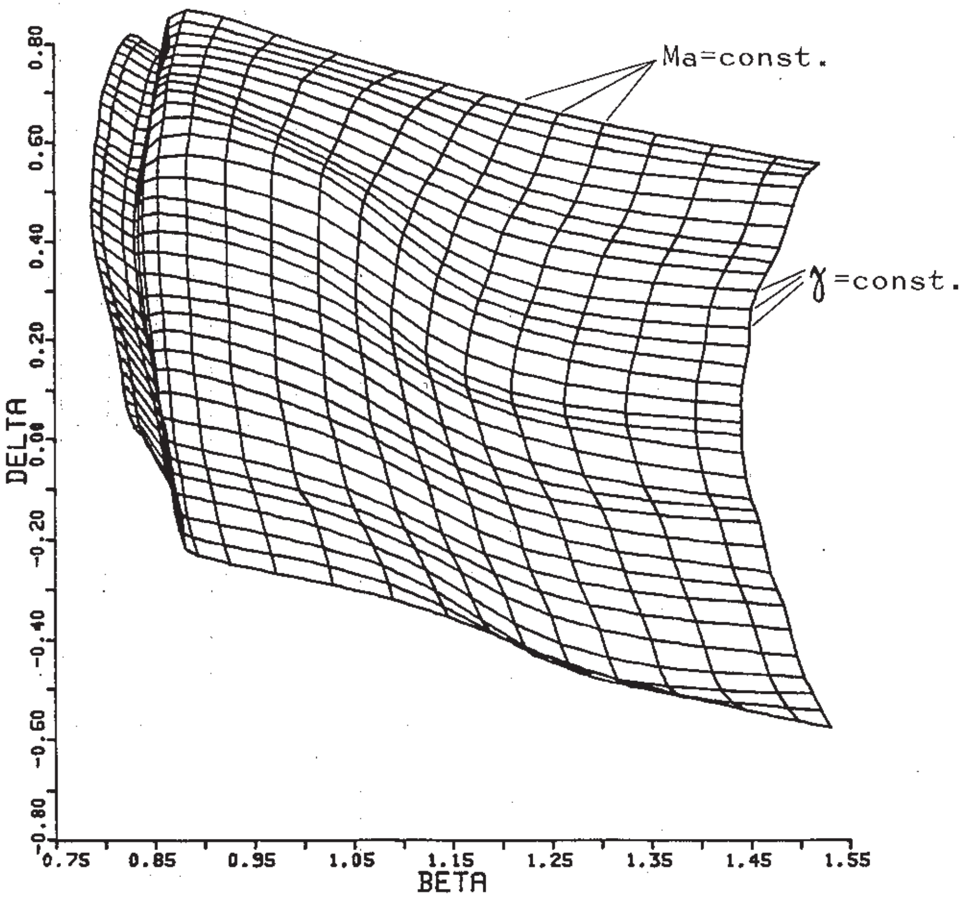
Ma=const.
γ=const.
DELTA
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
BETA
0.75
0.85
0.95
1.05
1.15
1.25
1.35
1.45
1.55

FIG. 16

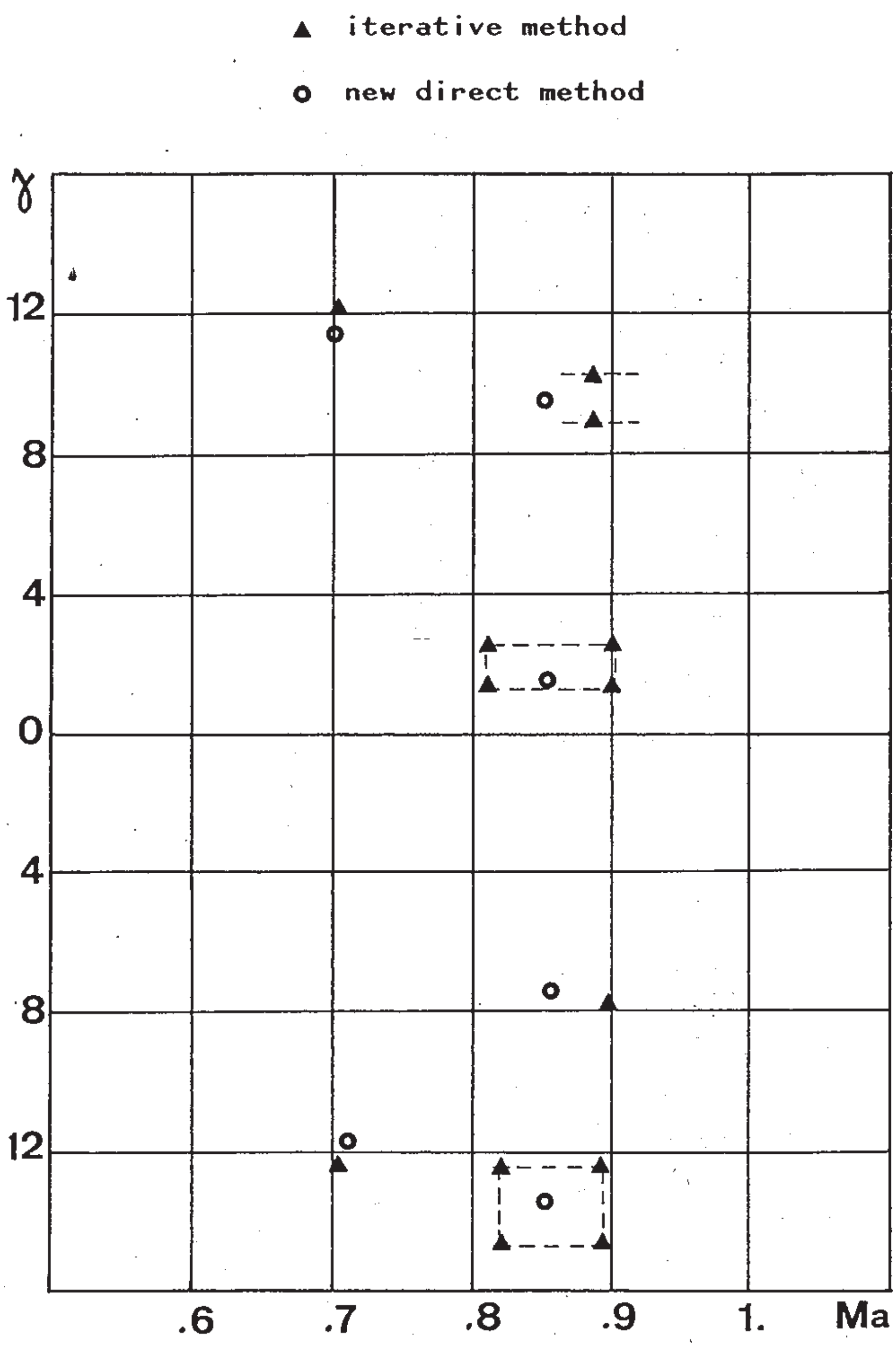

FIG. 17