A LASER ANEMOMETRY TECHNIQUE FOR MEASUREMENTS IN A SINGLE STAGE SUPERSONIC COMPRESSOR

by Isabelle TREBINJAC & André VOUILLARMET
Ecole Centrale de Lyon
B.P. 163 - 69131 ECULLY CEDEX
FRANCE

INTRODUCTION

A series of measurements has been carried out in a fully supersonic single-stage high-pressure compressor, using a "laser-two-focus" anemometer.

Such experimental investigation is a part of the general study of viscous flows in turbomachines. It provides a detailed knowledge of the local and complex phenomena such as leakage flow, viscous layers and shock-waves interaction. Furthermore it provides a data base for the validation of theoretical models presently under development in the laboratory.

In the first step we describe the new test-rig which has been built for this purpose, the characteristics of the investigated compressor and its adaptation to become accessible to measurements, and the experimental set-up.

Then, some particularities of our data acquisition and reduction procedures are presented, with references to the measurement in flow field having high absolute angle fluctuations.

Finally, some comparisons between L2F synchronized and non-synchronized measurements and the results obtained from pressure probes are presented downstream of the blade row.

DESCRIPTION OF THE TEST-RIG

Two years ago, a more powerful new compressor test-rig has been built in the Fluid Mechanic Laboratory of the Ecole Centrale de Lyon in order to drive the new generation of aeronautical compressor stages. It is composed of (figure 1) :

- a synchronous electric driving motor which design power is 2 Megawatts for a design rotating speed of 3 000 rev/mn ;

- a gear-box allowing compressor rotating speed up to 17 000 rev/min.

The aerodynamic circuit is an open one which can accept either axial or centrifugal machines.

Note that, because of the high power of the driving-motor, problems have been encountered related to the existence of eddy-currents impulses generated by the thyristors regulating system.

THE COMPRESSOR CHARACTERISTICS

- The investigations are carried out in a single-stage compressor built by the SNECMA Society which is representative of a first stage H.P. compressor of an advanced turbojet. It is composed of an inlet guide vanes, a rotor (with 48 blades) and a bladed diffuser.

At the design-point and for standard conditions the main characteristics of the machine are as follows :

. Maximum relative Mach number : 1.1 (near the hub) to 1.3 (near the tip)
. Hub-to-tip ratio at the inlet of the rotor : $\nu_i = 0.75$
. Design mass-flow : $\dot{m} \simeq 18$ kg/s
. Stagnation pressure ratio : $\pi = 1.84$
. Rotating speed : 16 000 rev/mn

- In order to perform laser-anemometer measurements eight specific windows have been mounted on the shroud of the machine, the eight corresponding measurement sections being presented figure 2.

- In order to avoid the soiling of the glasses, each window (figure 3.a) is provided with a cleaning device. Moreover, an original setting is mounted on each window to avoid problems related to the measurements near the shroud and especially in the rotating blade row :

- because of the crushing, by the blades, of the particles on the glass, the windows get dirty very quickly which decreases the signal-to-noise ratio ;

- furthermore, the flow field in this region is very sensitive to the least discontinuity of the wall which could be created by the presence of the window.

Then the glass is setting back to preserve air-tightness, and replaced by a perforated metal piece in continuity with the shroud (figure 3.b). The hole diameter is fitted according to the measurement point position.

THE EXPERIMENTAL SET UP

Measurements have been done using the Laser-Two-Focus Anemometer built in the laboratory, which main characteristics have been already described in the previous symposium in Genova (figure 4).

With regard to the last version, it has been modified by the adaptation of a polarization maintaining single-mode optical fiber which uncouples the laser supply from the optical arrangement.

Moreover new acquisition and reduction programs have been created allowing :

- a large versability concerning the data acquisition procedures especially in case of synchronized measurements ;

- an improvement of acquisition time with a real-time checking ;

- earnings in mass storage needs.

Some particularities of this software are now described.

DATA ACQUISITION AND REDUCTION PROCEDURES

The data acquisition is composed of two successive stages :

- a preliminary investigation
- the acquisition sequence itself

- The preliminary investigation consists in an acquisition realized with a reduced number of data.

We remind that, when using a counting technic, the wrong data arising from two different particles crossing the two spots, have representative velocity histogram located in a velocity range which is different from that representative of valid data. So, the first aim of the preliminary acquisition is to determine the velocity range in which the informations are considered as valid.

At the same time we have to determine the range of the angles to be explored.

This first stage offers a large versatility, giving the possibility after a first scanning :

- to simply remove or to do again some angle when anomalies occured during the acquisition,

- to complete the scanning with new angles when the initial range was too narrow or ill-chosen.

- In the case of synchronized measurements, the informations must be classified in terms of their azimutal position in the rotating frame. For this purpose, the blade pitch is splitted in a variable number of intervals which widths can be chosen independently each other in order to adjust the spatial resolution to the nature of the flow (large intervals in uniform flow field regions and narrow intervals in high-gradient zones).

Furthermore, it is possible to choose the number of valid data independently for each azimutal position which allows to keep an adequate accuracy even in zones presenting seeding deficiency (in wake regions for instance).

This versatility is very interesting when measurements are performed on high-power (then high-cost) test-rigs where we have to reduce the acquisition time. An illustration will be shown in the last part of this presentation.

- Either during synchronized or averaged measurements two acquisition procedures can be used : the first one which is named "complete" and the second one named "simplified".

\+ The complete procedure is the wellknown one which consists in establishing, from the measurements, a two-dimensional probability histogram $N_{ij}(\alpha_j, V_i)$ where α_j and V_i are respectively the angle and the modulus of the absolute vector velocity $\overrightarrow{V_{ij}}$.

The corresponding data reduction is based on the classical statistical treatment of two-dimensional random data, where the averaged values of the two cartesian componants u and v of the velocity vector can be expressed from the normalized probability density function $P(u,v)$ by :

$$\bar{u} = \iint u \, P(u,v) \, du \, dv$$

$$\bar{v} = \iint v \, P(u,v) \, du \, dv$$

or, after transformation of the random variables (whose Jacobian is V)

$$\bar{u} = \iint u \, P(V,\alpha) \, dV \, d\alpha$$

$$\bar{v} = \iint v \, P(V,\alpha) \, dV \, d\alpha$$

so

$$\bar{V}^2 = \bar{u}^2 + \bar{v}^2$$

$$tg\,\bar{\alpha} = \bar{u}/\bar{v}$$

This formulation leads to :

$$tg\,\bar{\alpha} = \frac{\Sigma_i \Sigma_j \; V_i \sin\alpha_j \, . \, N_{ij}}{\Sigma_i \Sigma_j \; V_i \cos\alpha_j \, . \, N_{ij}}$$

$$\bar{V}^2 = \frac{1}{(\Sigma_i \Sigma_j N_{ij})^2}\left[(\Sigma_i \Sigma_j V_i \sin\alpha_j . N_{ij})^2 + (\Sigma_i \Sigma_j V_i \cos\alpha_j . N_{ij})^2\right]$$

We can notice that this result can be directly obtained, by carrying out a vectorial average of the individual velocity vectors :

$$\overline{\overrightarrow{V}} = \frac{\Sigma_i \Sigma_j N_{ij} \overrightarrow{V_{ij}}}{\Sigma_i \Sigma_j N_{ij}}$$

This procedure is rigorous if the number of informations is large enough but time-consuming, which is financially prejudicial when the measurements are performed on a high power test-rig.

+ In order to reduce the acquisition-time, the simplified procedure can be used. It consists in calculating the value of the mean absolute angle $\bar{\alpha}$, during the preliminary step. Then a single acquisition realized at this mean-angle $\bar{\alpha}$ leads to the determination of the averaged value of the velocity modulus $\bar{V}$. This procedure is reliable as far as the velocity fluctuations are not too large.

SOME MEASUREMENTS DOWNSTREAM THE BLADE ROW

Measurements have been taken at about one hundred and fifty points, including more than one hundred inside the rotating blade row. We present a comparison between a first series of L2F averaged values of the absolute angle $\bar{\alpha}$ (figure 5) and velocity $\bar{V}$ (figure 6) with the results obtained from two kinds of pressure probes downstream of the blade row (section 6). We observe a good agreement except in the parietal zones and especially near the shroud where the secondary flows are not correctly registered.

In order to explain these differences an other series of synchronized measurements have been performed and can be shown for two locations (stars on figure 2) :

- in mid-channel ($R^* = \dfrac{R - R_h}{R_t - R_h}$ = 46.27 %) at $x \simeq$ 60 % of the axial chord downstream of the trailing-edge,
- and near the shroud (R^* = 92.15 %) at $x/c_{ax} \simeq$ 39 %,

. **In mid-channel.**

The azimutal evolutions of the absolute parameters (V and α), the relative parameters (W , β and the standard deviations σ_β , σ_W) are presented figures 7 to 11, where the continuous lines correspond to a regular splitting of the blade pitch, and the dotted lines to a variable interval width splitting (narrower in the wake region and larger in the "inviscid" flow region).

- On the figure 9, we clearly observe a rather narrow wake region which is better described by the dotted line because of the less azimutal integrated effect without, either spoiling the accuracy in the "inviscid" region, or increasing too much the acquisition-time.

Moreover, for the azimutal position $R\theta/g$ = 12.5 %, we point out an absolute angle probability histogram $P(\alpha)$ (figure 12) with two separate peaks which leads to two possible different values of the mean angle $\bar{\alpha}$ and then of the relative parameters $\bar{W}$ and $\bar{\beta}$. One of these corresponds to a wake value and the other one to an "inviscid" flow value, which is explained by an oscillation of the wake boundary.

- On the figure 10, we note an increasing of β in the wake region, the gradient outside of it being that measured in the row (β'_2 is the blade angle at the outlet of the row).

- The evolutions of the standard deviations σ_β and σ_W (figure 11) confirm the wake location.

. Near the shroud

The azimutal evolutions of the absolute parameters (V and α), the relative parameters (W and β) and the particles distribution N are presented figures 13 to 17.

We observe that, in this case, the wake region covers about 50 % of the pitch. This can be explain by secondary flows, tip clearance effect or possible blade boundary layers separation due to the shock-wave interaction.

This large wake region can be pointed out, in an other way, by the angle probability histogram (figure 18) obtained during non-synchronized measurements, where we can see two separate peaks, the one around 54 degrees corresponding to the "inviscid" flow region and the other around 70 degrees corresponding to the wake.

. Comparisons between the averaged values obtained by different ways

So if the angle scanning range, during the acquisition procedure, is not large enough, only one peak may be taken into account, that leads to shifted values as previously presented near the shroud on figures 5 and 6. This cause of error is all the more likely as the second peak (wake peak) spreads out a wide range of angles with a low amplitude. If the whole histogram is considered, then we obtain a rather good agreement between the probes values and the one calculated from the synchronised measurements (values weighted by the number of particles) represented figures 5 and 6 by a square point. At mid-channel the wake is too narrow to generate this type of error which explains the good agreement previously observed.

In view of these observations, different averaged values are compared on the figures 7 to 10 and 13 to 16 :

- those obtained for $\mathcal{R}^* = 46.27$ %, with the "simplified" and "complete" procedures for the inviscid flow only, which are both in good agreement with synchronized values ;

- those obtained for $\mathcal{R}^* = 92.15$ % with the "simplified" procedure either for the "inviscid" flow or for the wake region which are still consistent.

The meaning of the different averaged values, presented on the right-side of the figures, is given table 1.

CONCLUSION

- It has been shown that the L-2F technique can present some difficulties increasing the acquisition-time or can lead to a shifted evaluation of the averaged parameters when the investigated flow field presents large absolute angle gradients (wake regions behing a rotating blade row or separated flow).

- In this case the possibility of choosing independently the widths of the azimutal intervals allows to better describe the high-gradient zones without increasing too much the acquisition time.

- For this flow configuration, the "simplified" procedure leads to consistent results while decreasing the acquisition-time.

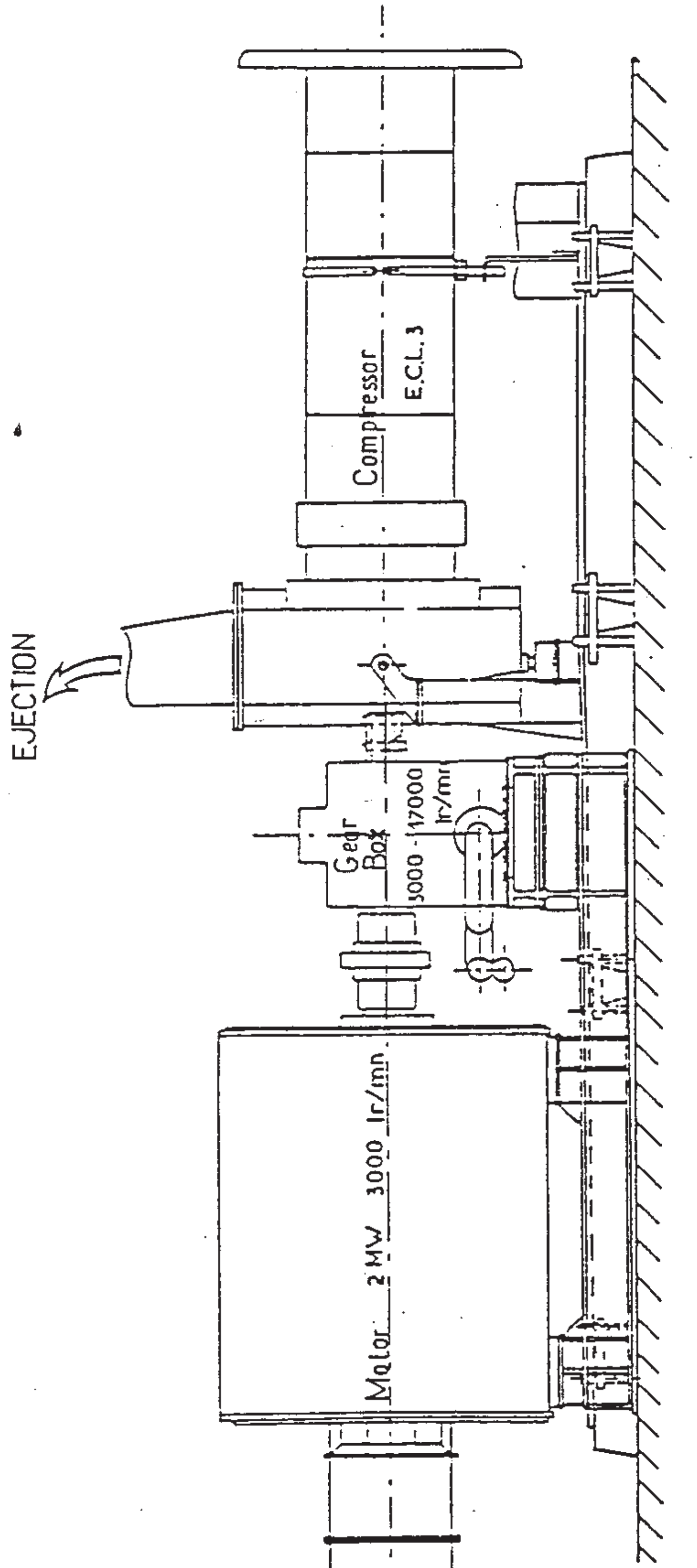

EJECTION
Compressor
E.C.L. 3
Gear Box
3000 - 17000 tr/mn
Motor 2 MW 3000 tr/mn

Figure 1

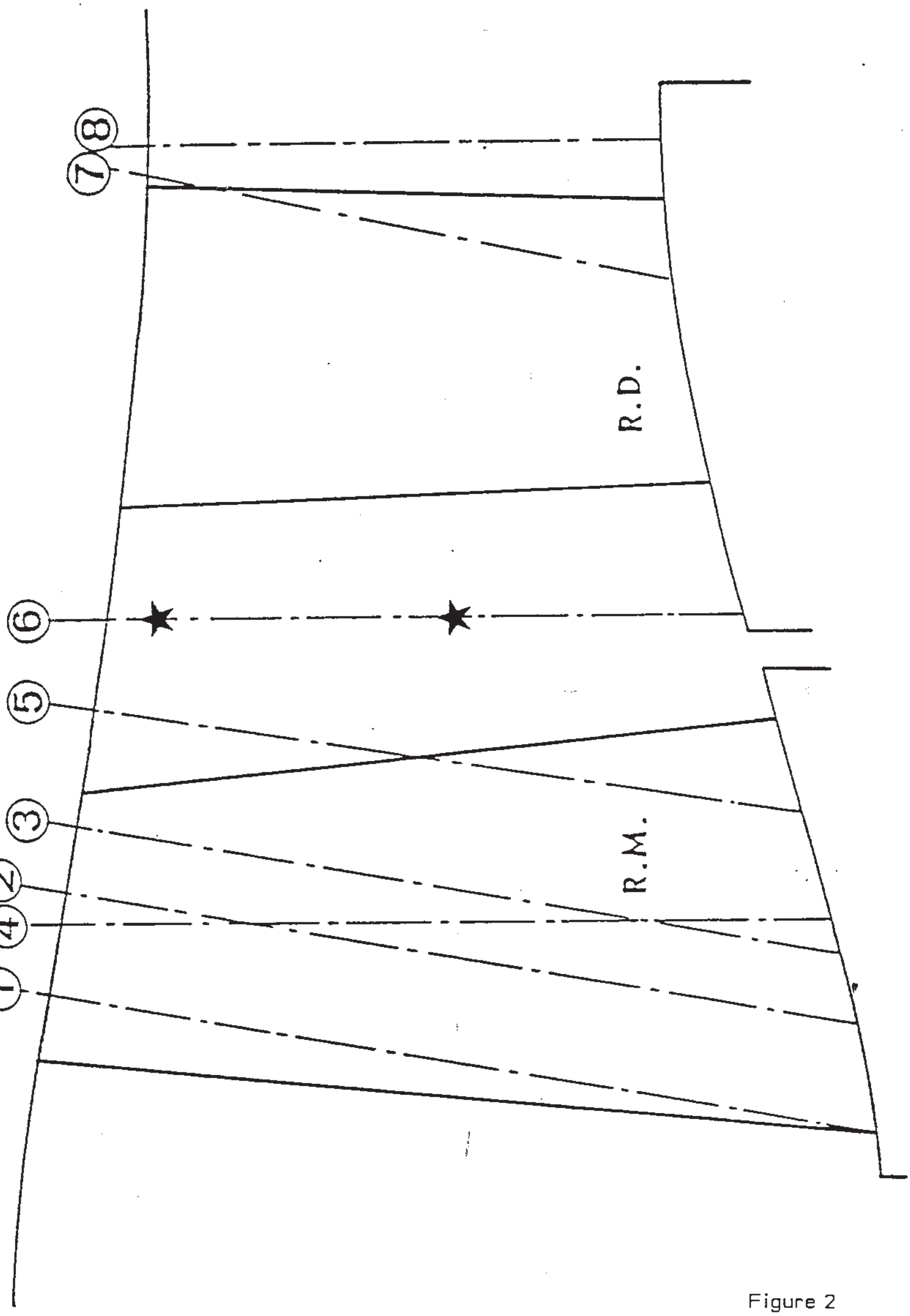
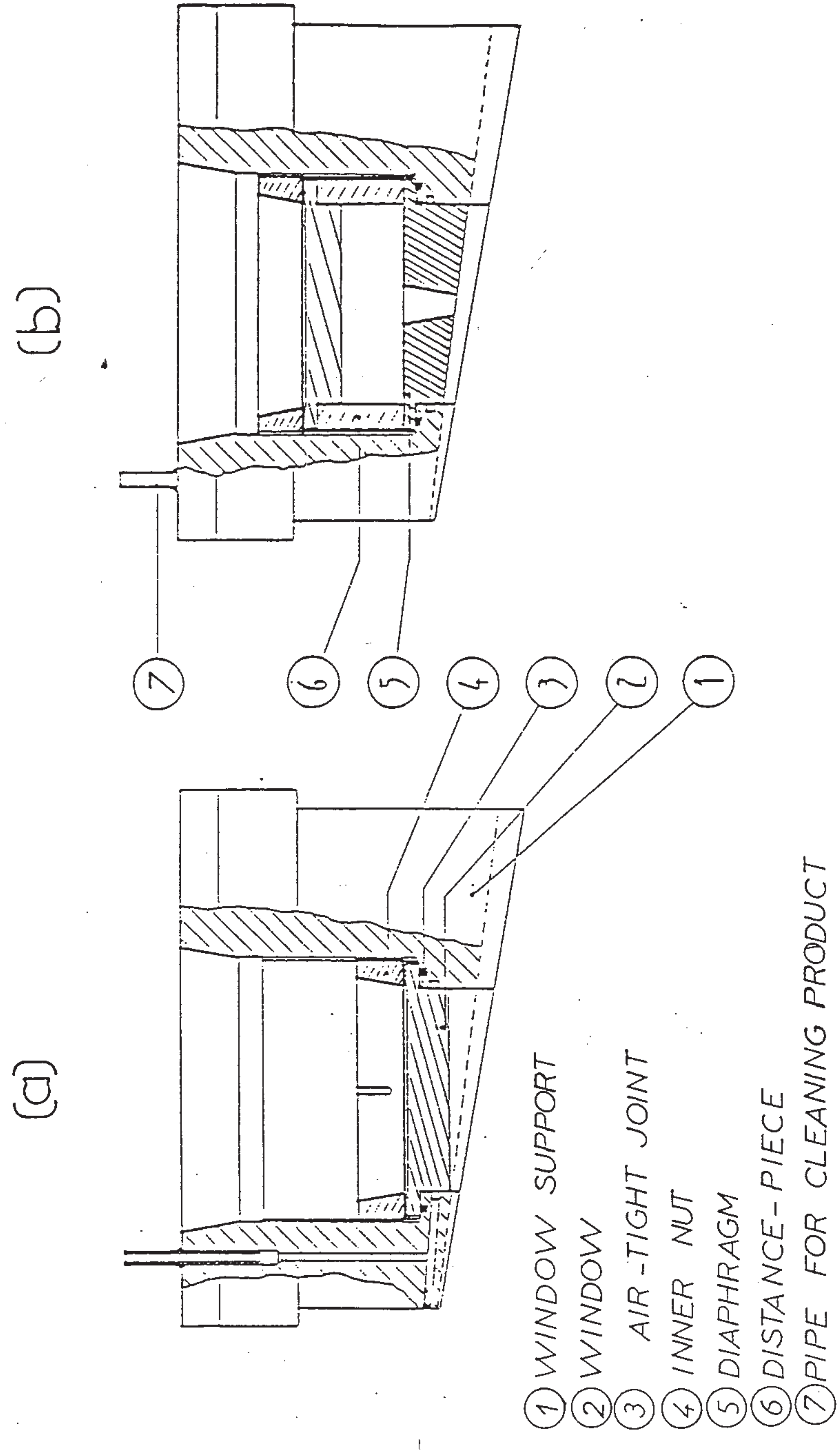


Figure 2



(a)
(b)
1 WINDOW SUPPORT
2 WINDOW
3 AIR-TIGHT JOINT
4 INNER NUT
5 DIAPHRAGM
6 DISTANCE-PIECE
7 PIPE FOR CLEANING PRODUCT

Figure 3

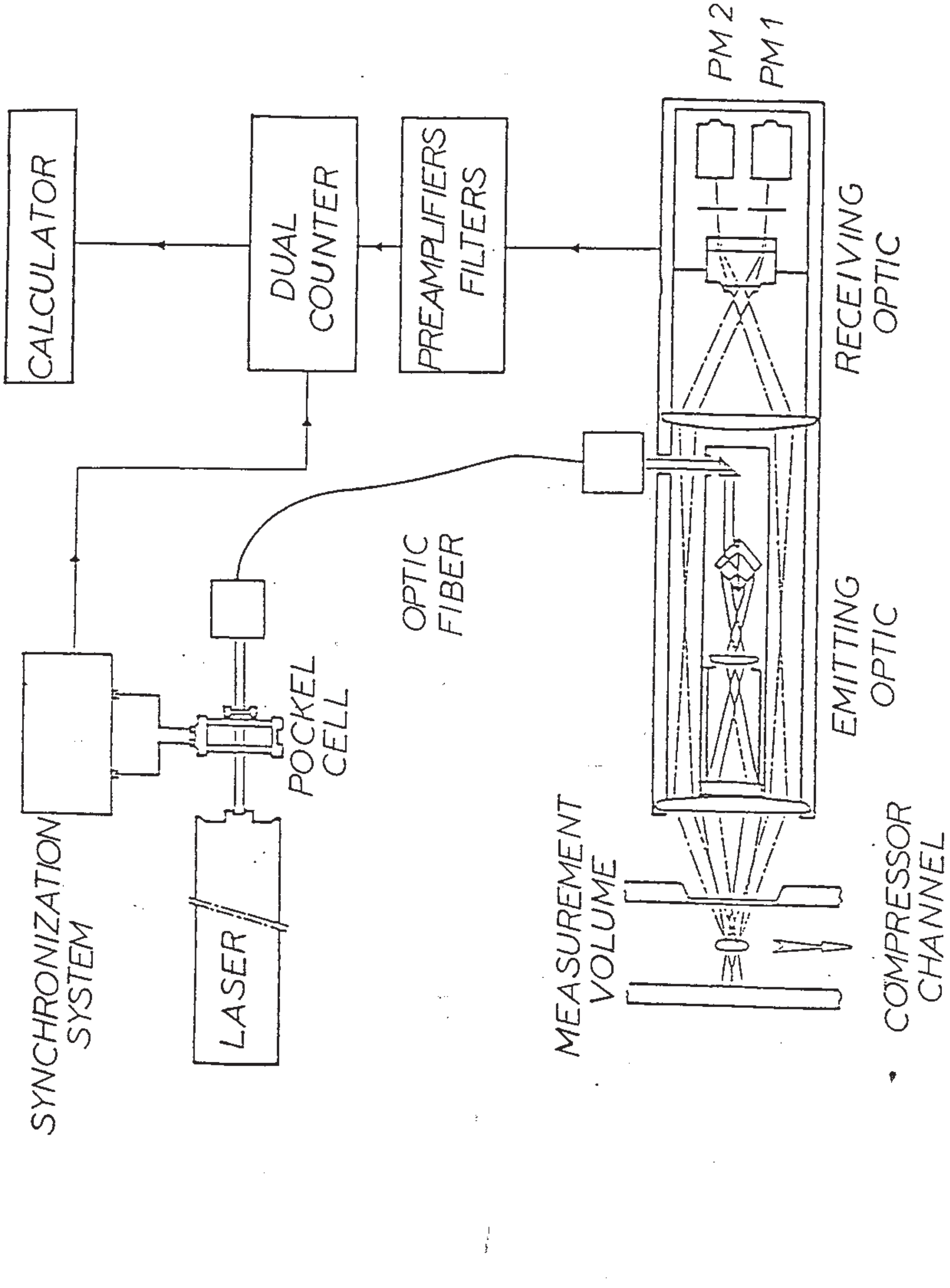

CALCULATOR
DUAL COUNTER
PREAMPLIFIERS FILTERS
PM 2
PM 1
RECEIVING OPTIC
SYNCHRONIZATION SYSTEM
OPTIC FIBER
POCKEL CELL
LASER
EMITTING OPTIC
MEASUREMENT VOLUME
COMPRESSOR CHANNEL

Figure 4

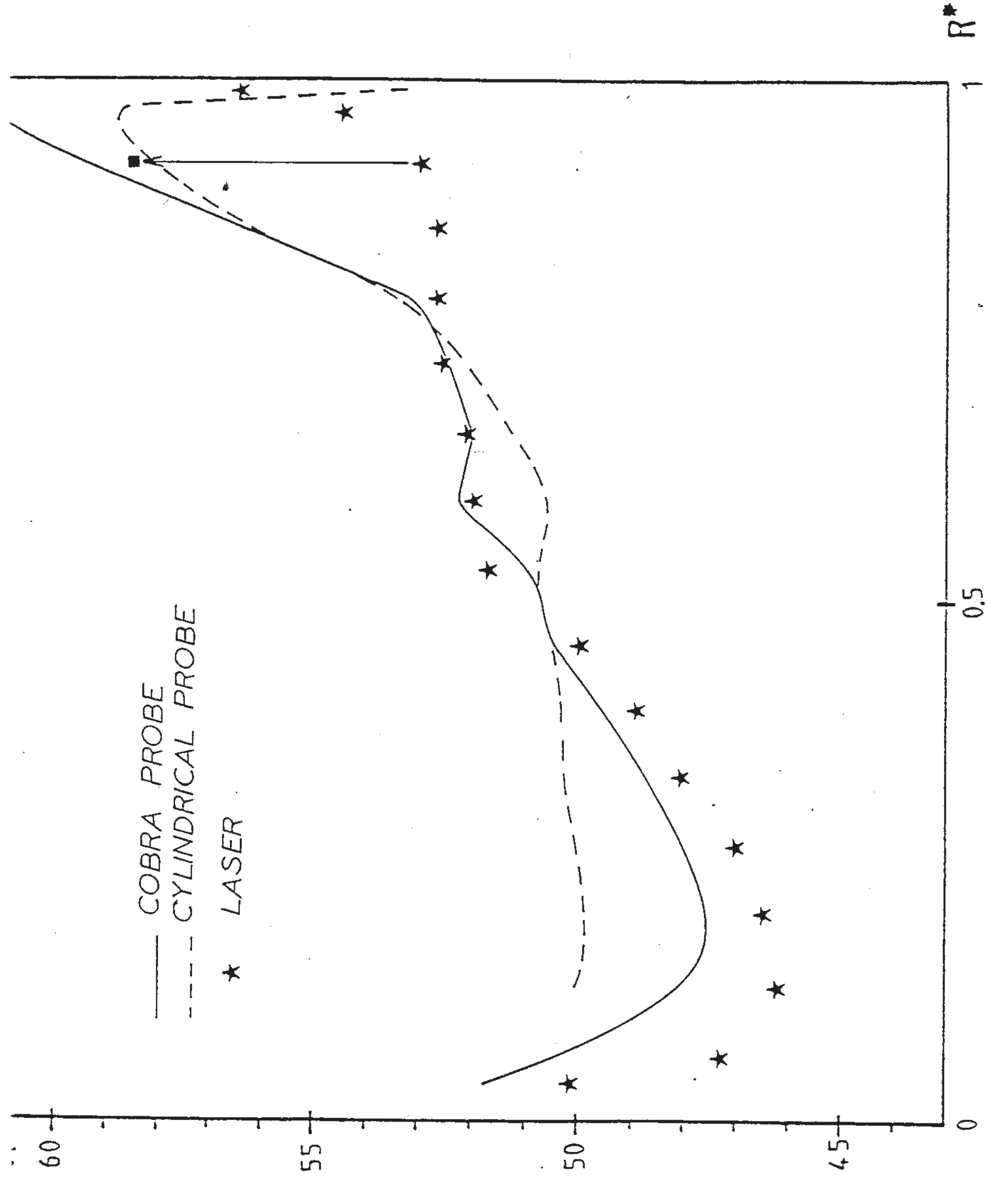


Figure 5

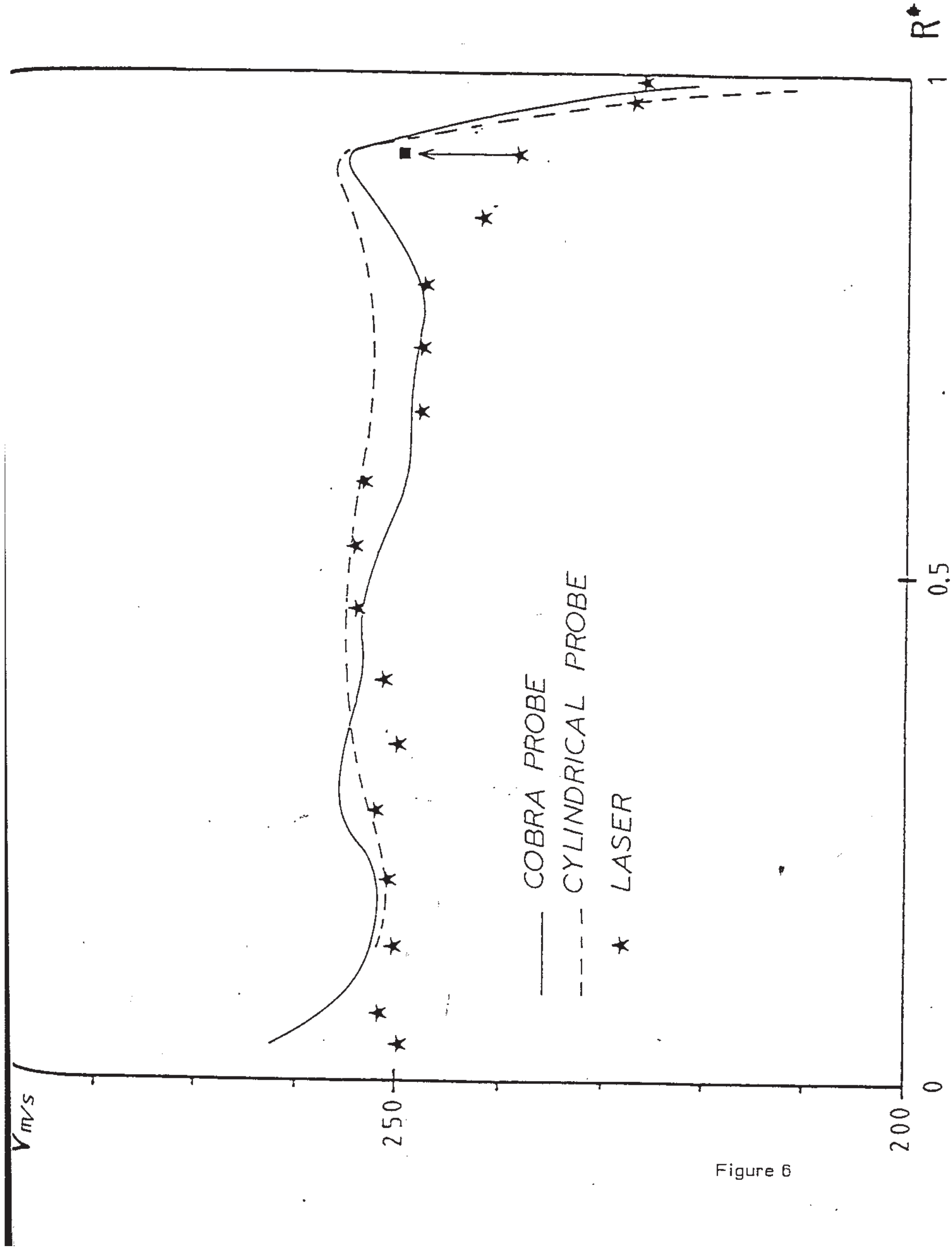


Figure 6

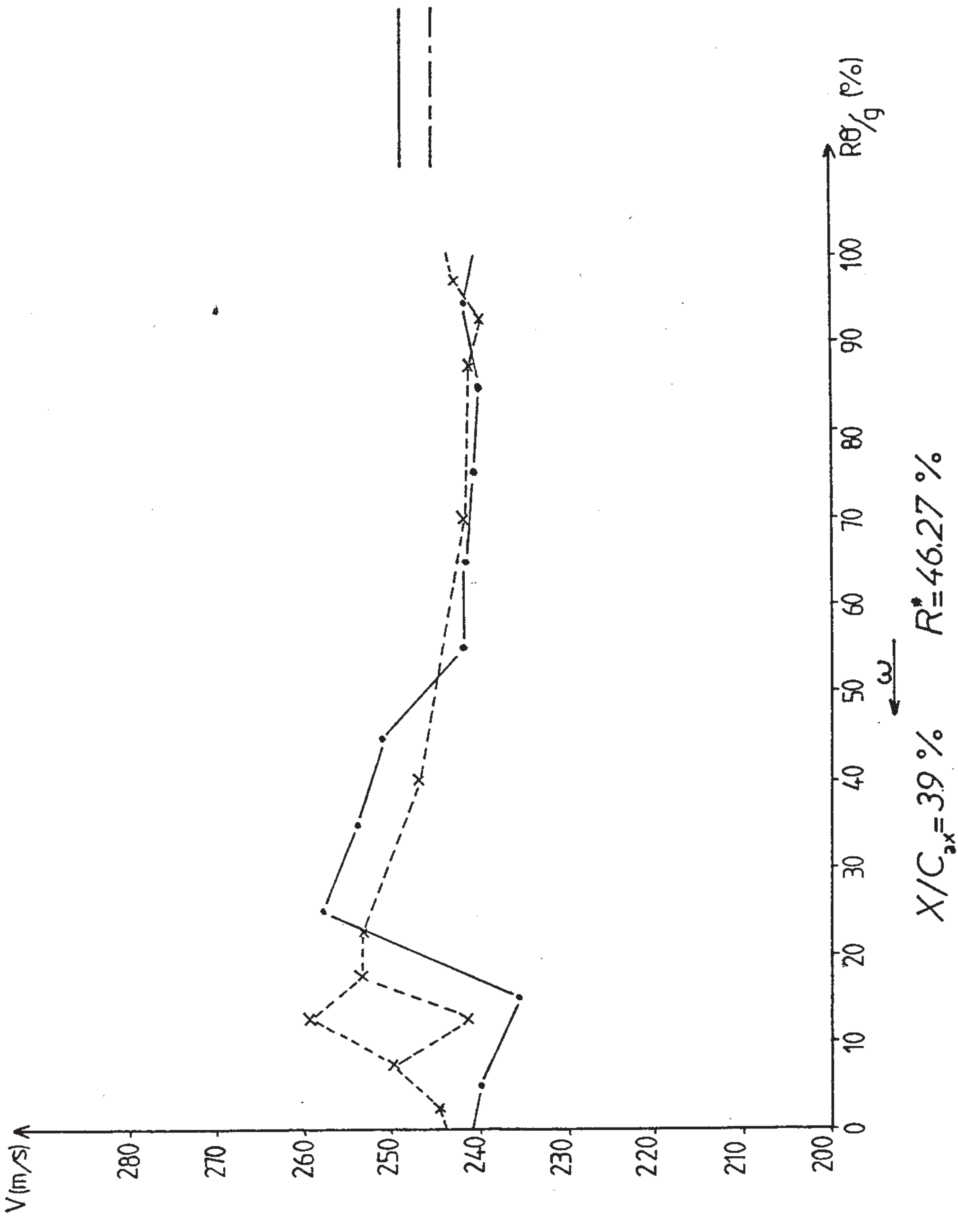

V(m/s)
280
270
260
250
240
230
220
210
200
0
10
20
30
40
50
60
70
80
90
100
Rθ/g (%)
ω
X/C_ax = 39 %
R* = 46.27 %

Figure 7

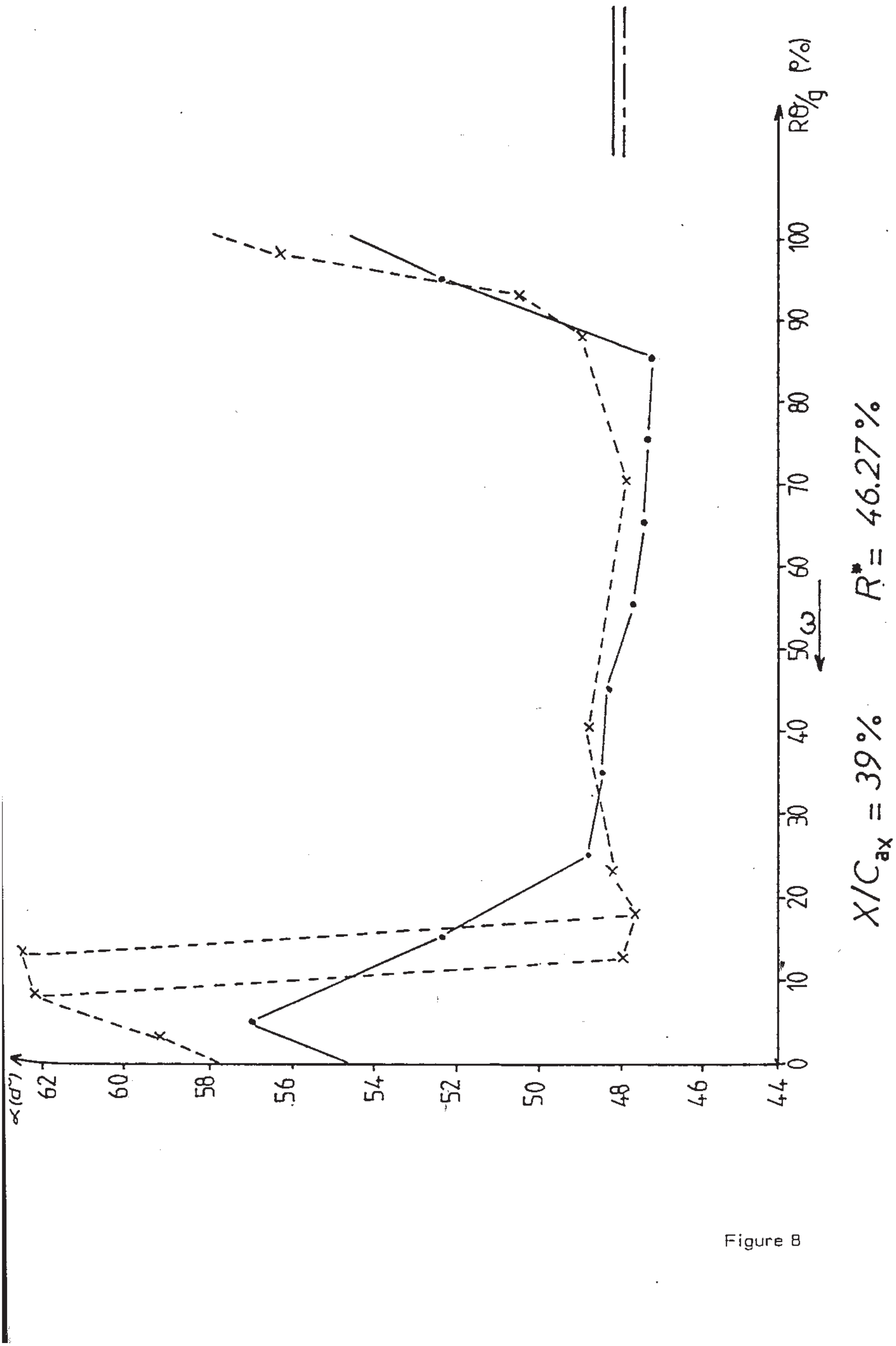

X/C_ax = 39 %
R* = 46.27 %
ω
α (d°)
RΘ/g P/o
0
10
20
30
40
50
60
70
80
90
100
44
46
48
50
52
54
56
58
60
62

Figure 8

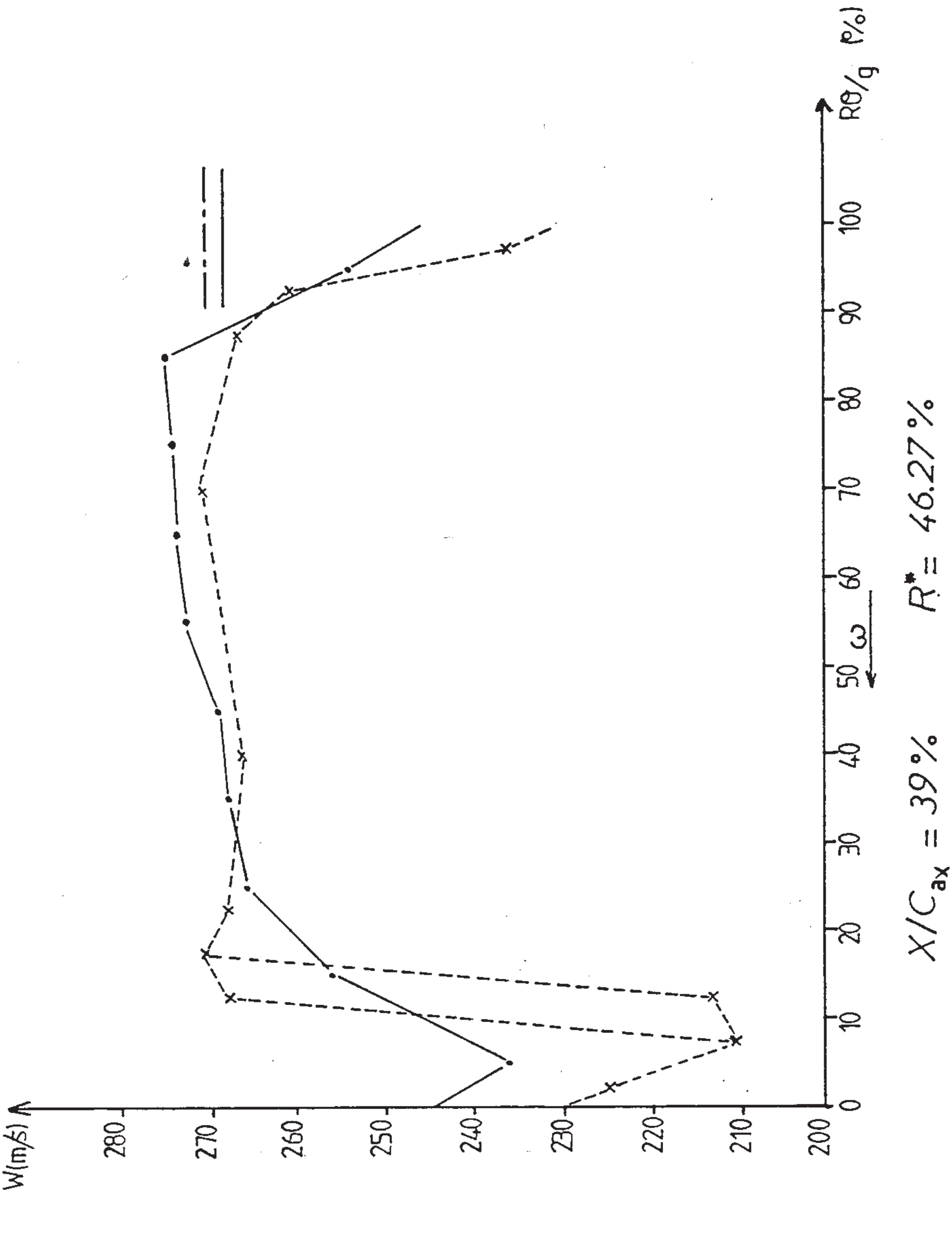
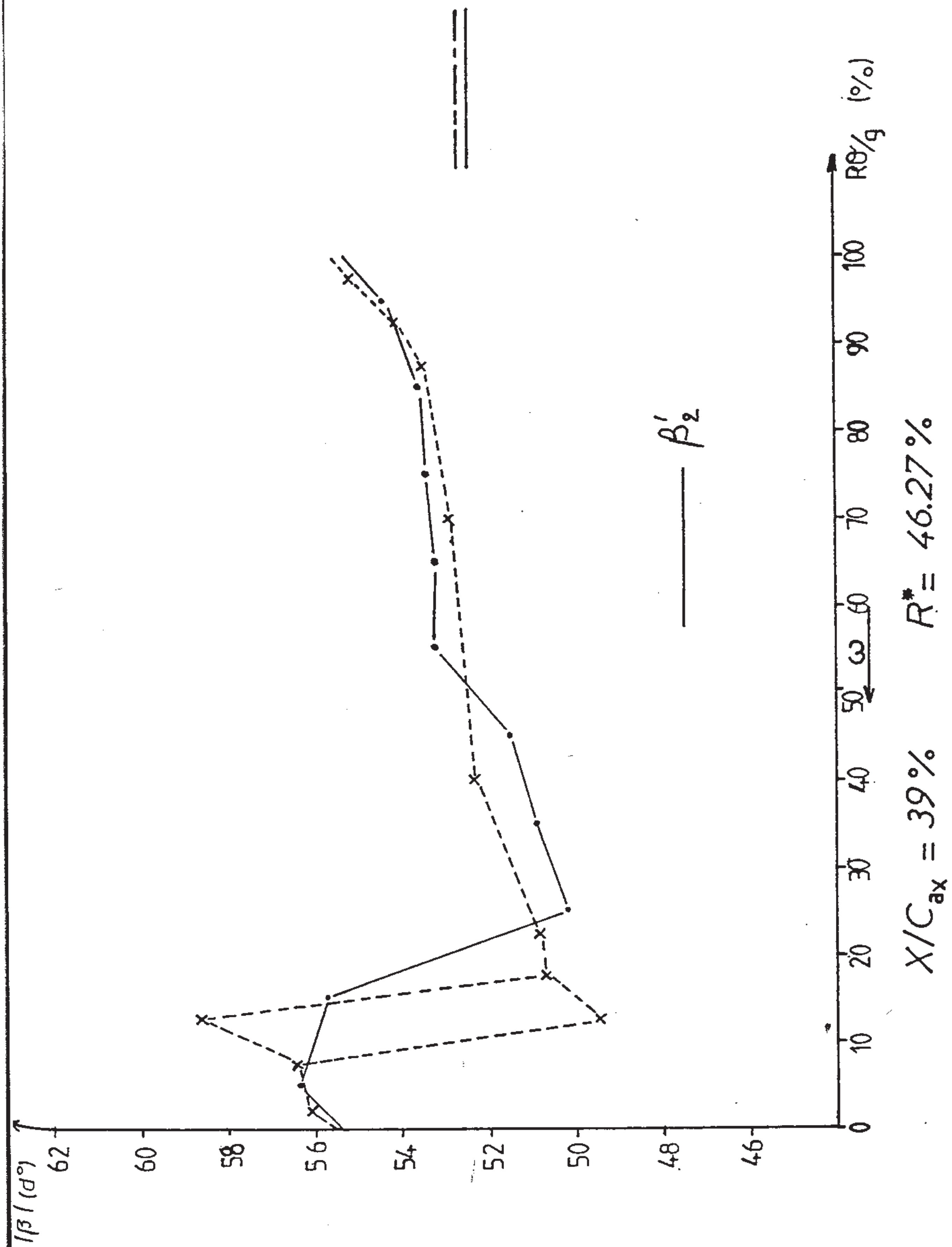
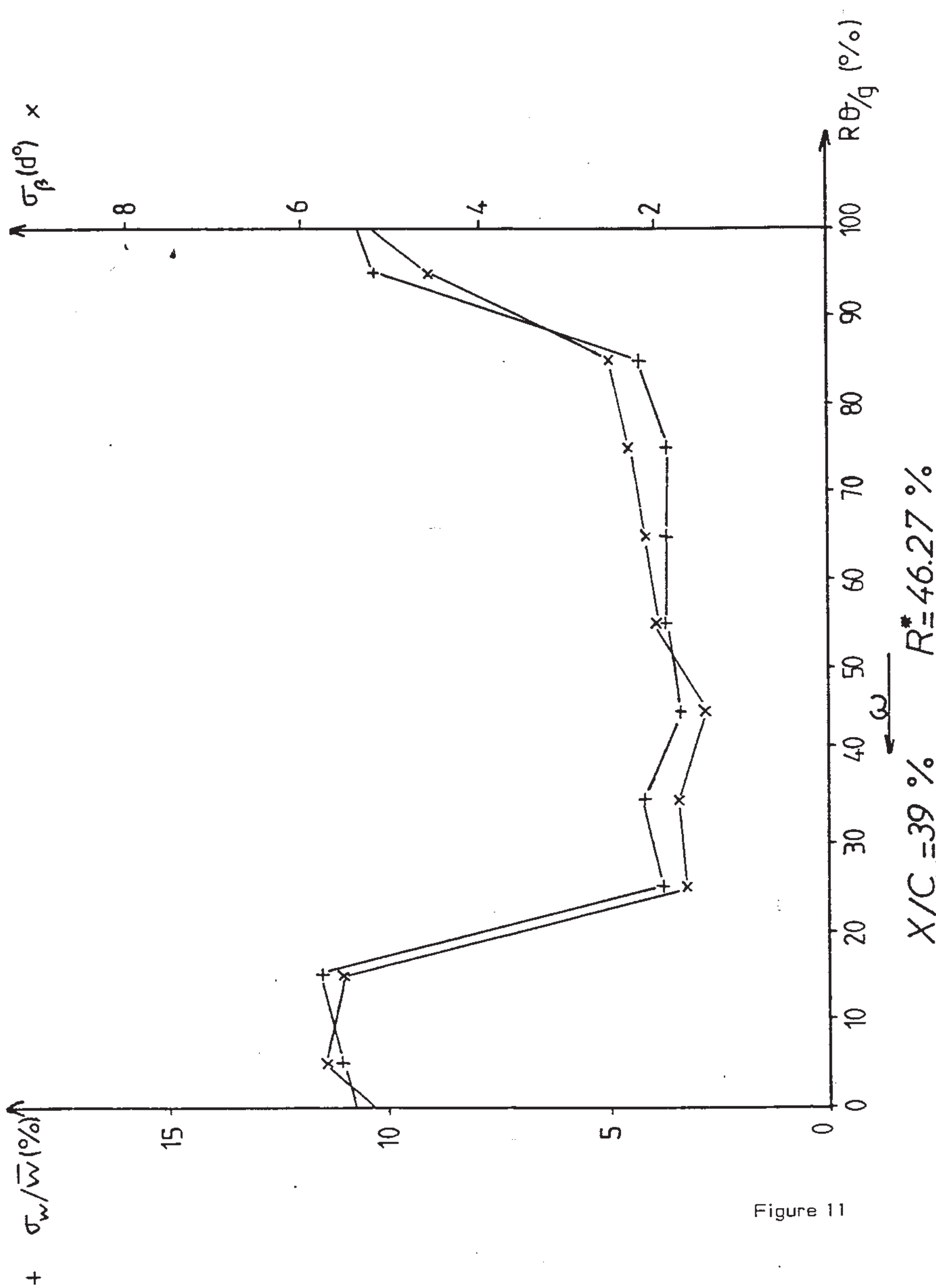

W(m/s)
280
270
260
250
240
230
220
210
200
0
10
20
30
40
50
60
70
80
90
100
Rθ/g (%)
ω
X/C_ax = 39%
R* = 46.27%

Figure 9



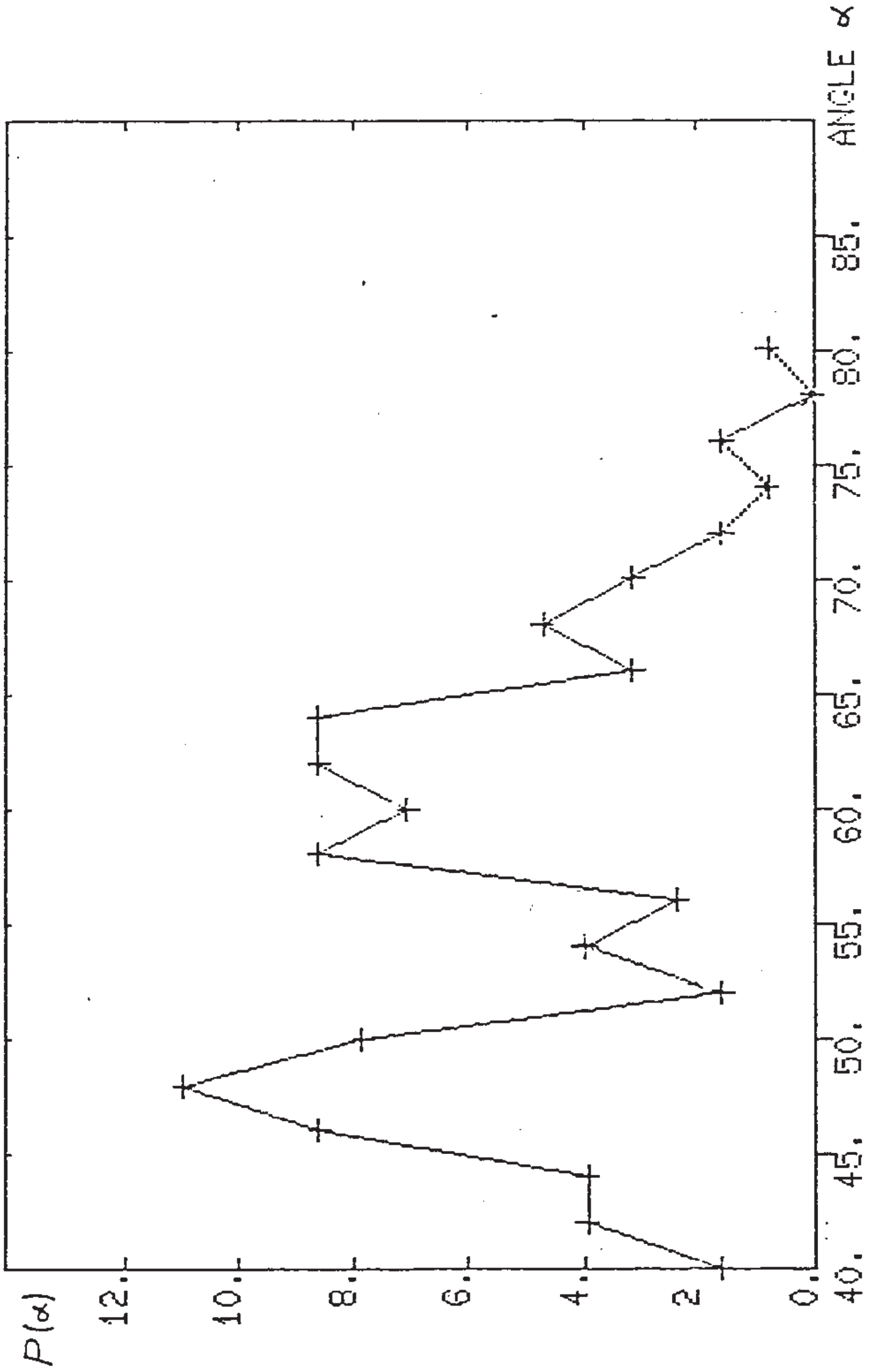
|β| (d°)
62
60
58
56
54
52
50
48
46
0
10
20
30
40
50
60
70
80
90
100
Rθ/g (%)
ω
β'2
X/Cax = 39%
R* = 46.27%

Figure 10



$\sigma_\beta (d^o)$ ×
$\sigma_w/\overline{W}$ (%) +
$R\theta/g$ (%)
X/C_{ax}=39 %
R^*=46.27 %
ω
8
6
4
2
15
10
5
0
0
10
20
30
40
50
60
70
80
90
100

Figure 11



ANGLE PROBABILITY HISTOGRAM : AZIMUT 3 $R^{*} = 46,27\ \%$

Figure 12

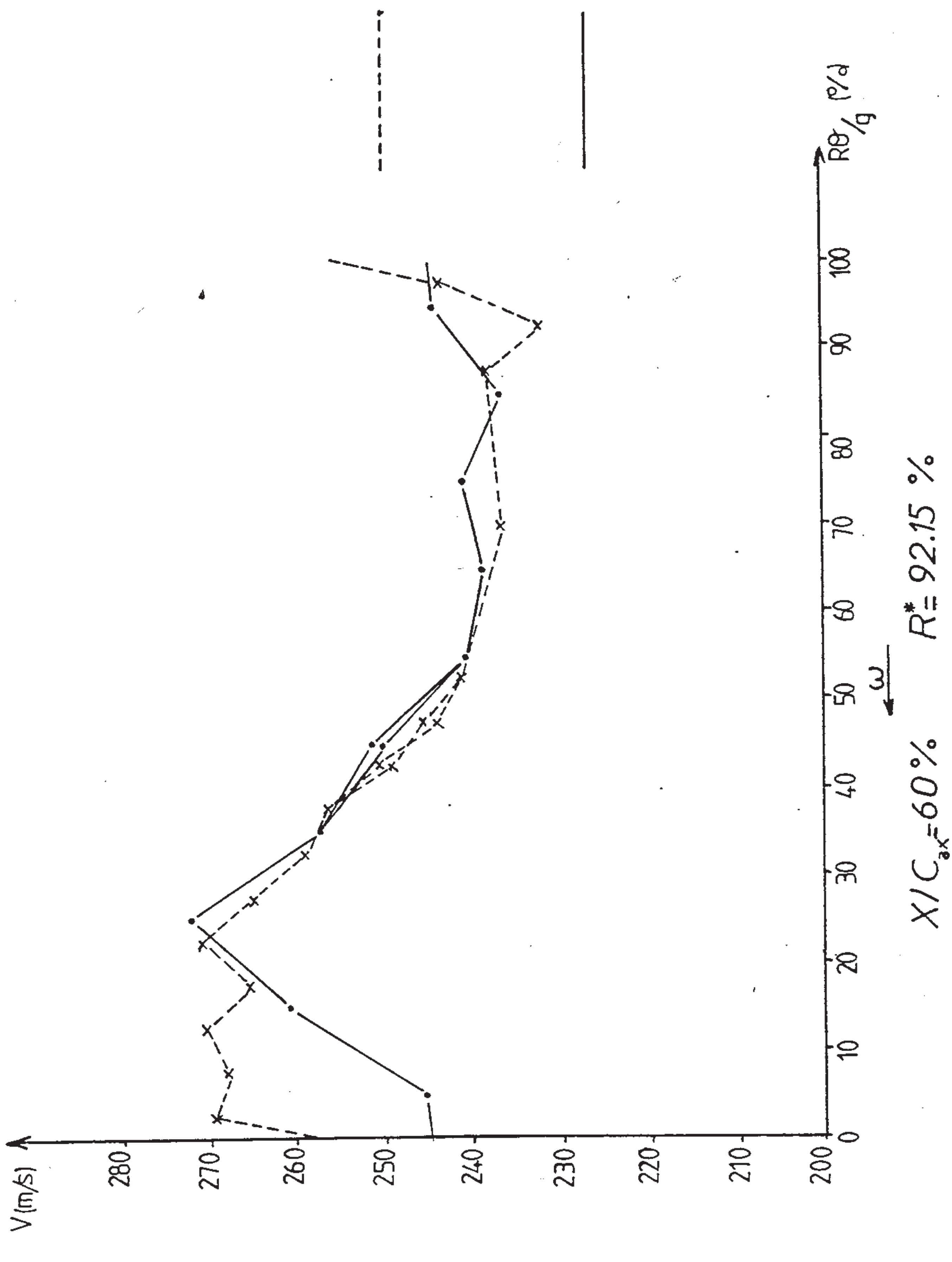
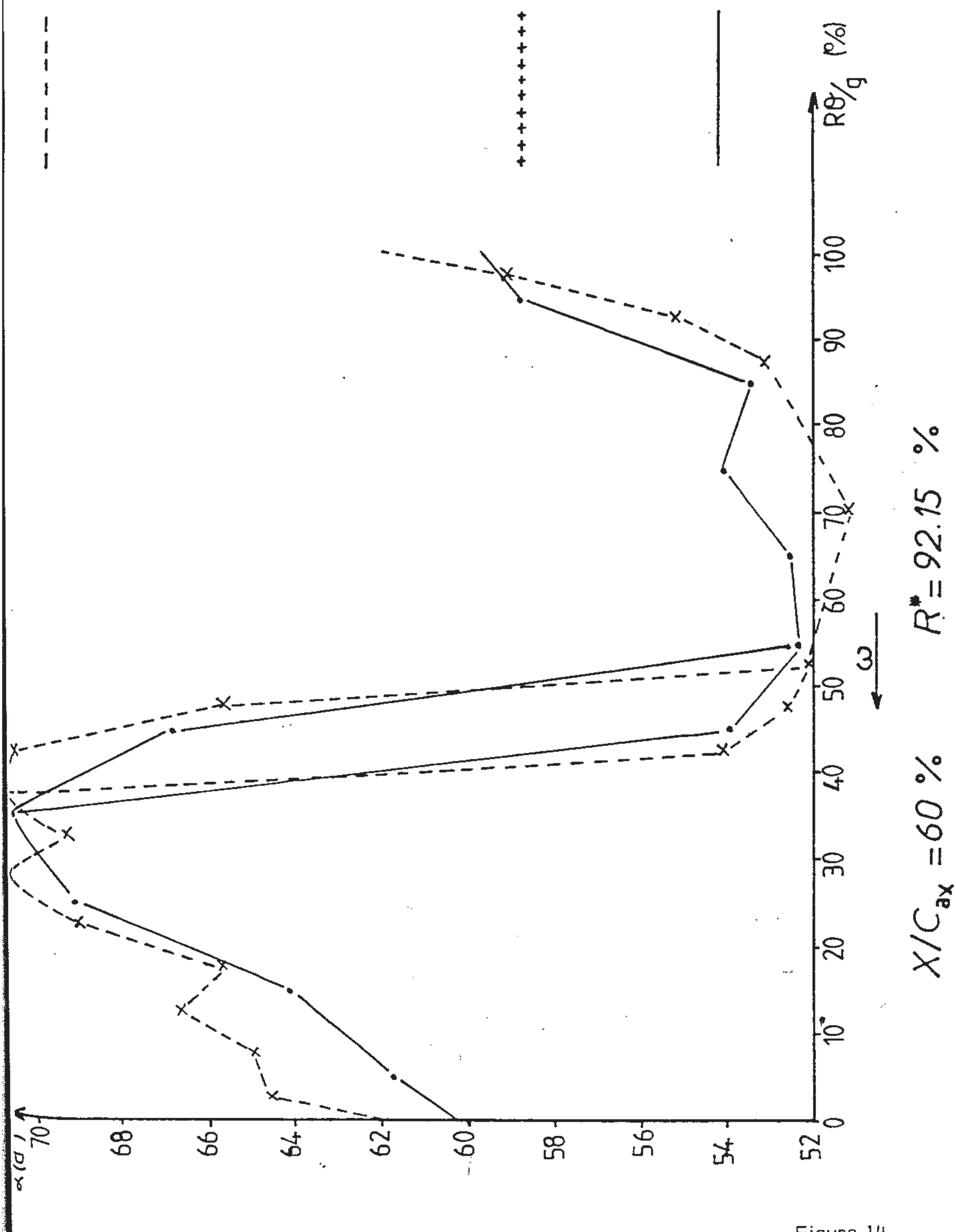

V(m/s)
280
270
260
250
240
230
220
210
200
0
10
20
30
40
50
60
70
80
90
100
Rθ/g (%)
ω
X/C$_{ax}$=60%
R*= 92.15 %

Figure 13



Rθ/g (%)
X/Cax =60 %
R* = 92.15 %
ω
0
10
20
30
40
50
60
70
80
90
100
52
54
56
58
60
62
64
66
68
70

Figure 14

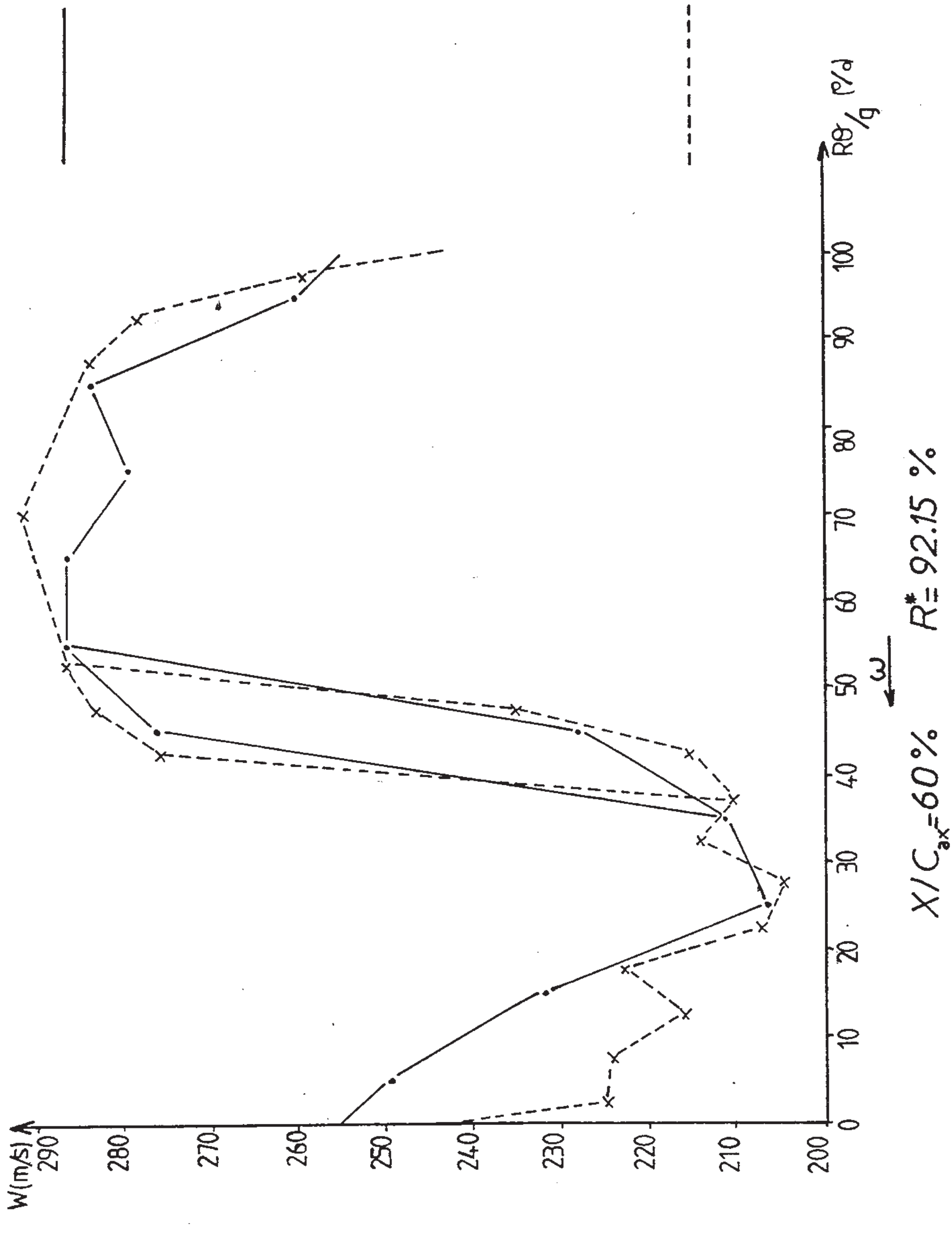

W(m/s)
290
280
270
260
250
240
230
220
210
200
0
10
20
30
40
50
60
70
80
90
100
Rθ/g (%)
ω
X/C_ax=60%
R*= 92.15 %

Figure 15

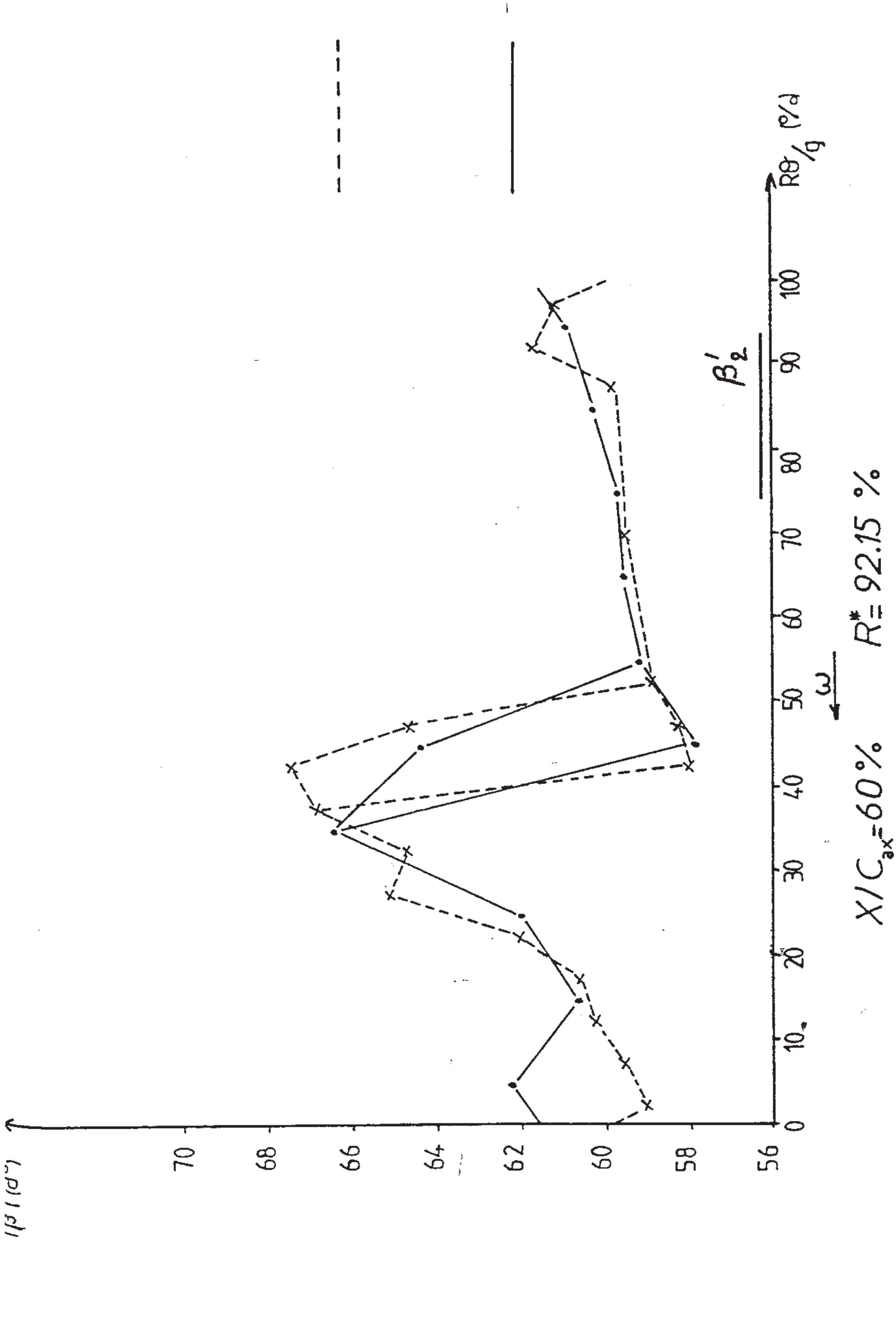

|β| (d°)
70
68
66
64
62
60
58
56
0
10
20
30
40
50
60
70
80
90
100
Rθ/q (%)
β'2
ω
X/Cax=60%
R*= 92.15 %

Figure 16

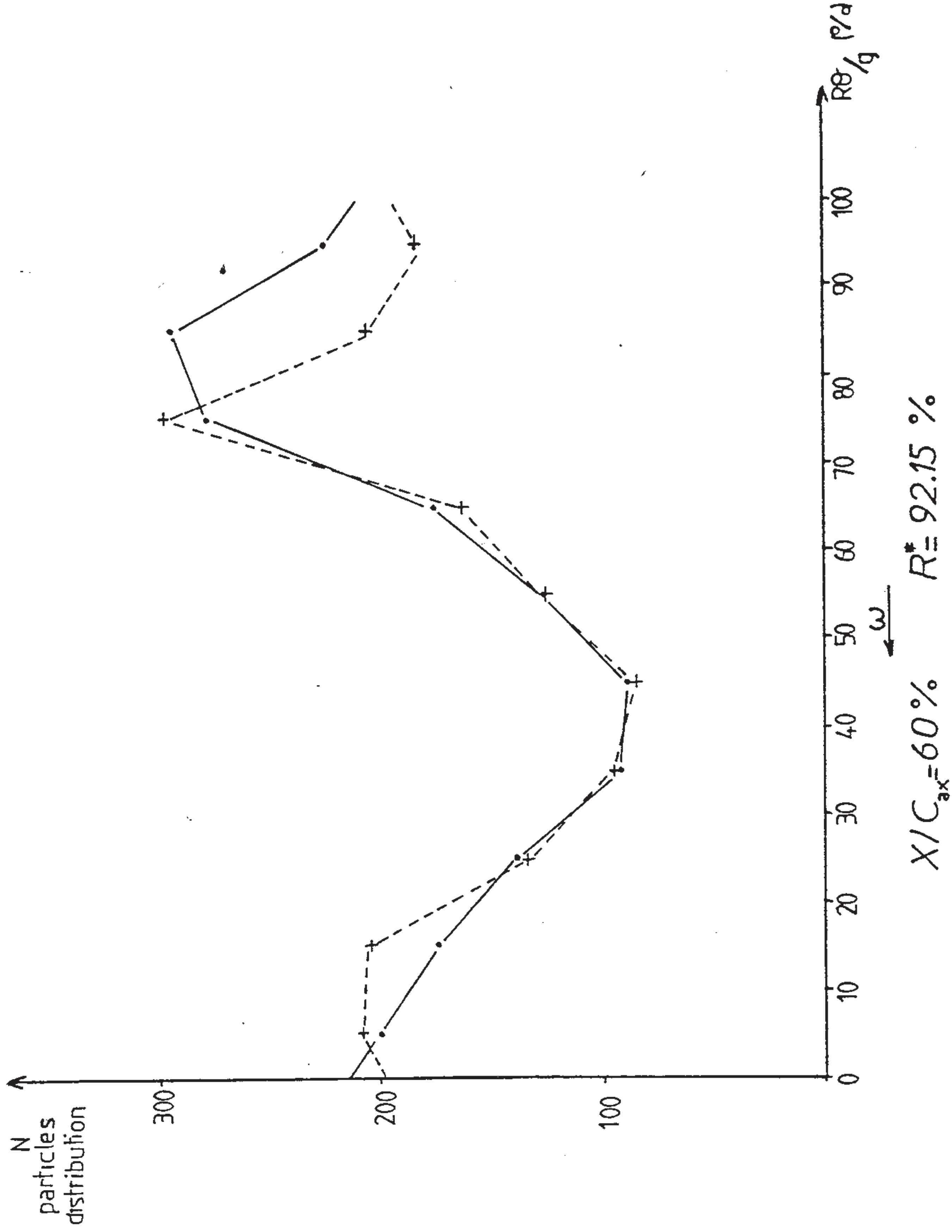

N
particles
distribution
300
200
100
0
10
20
30
40
50
60
70
80
90
100
Rθ/g (%)
ω
X/Cax=60%
R*= 92.15 %

Figure 17

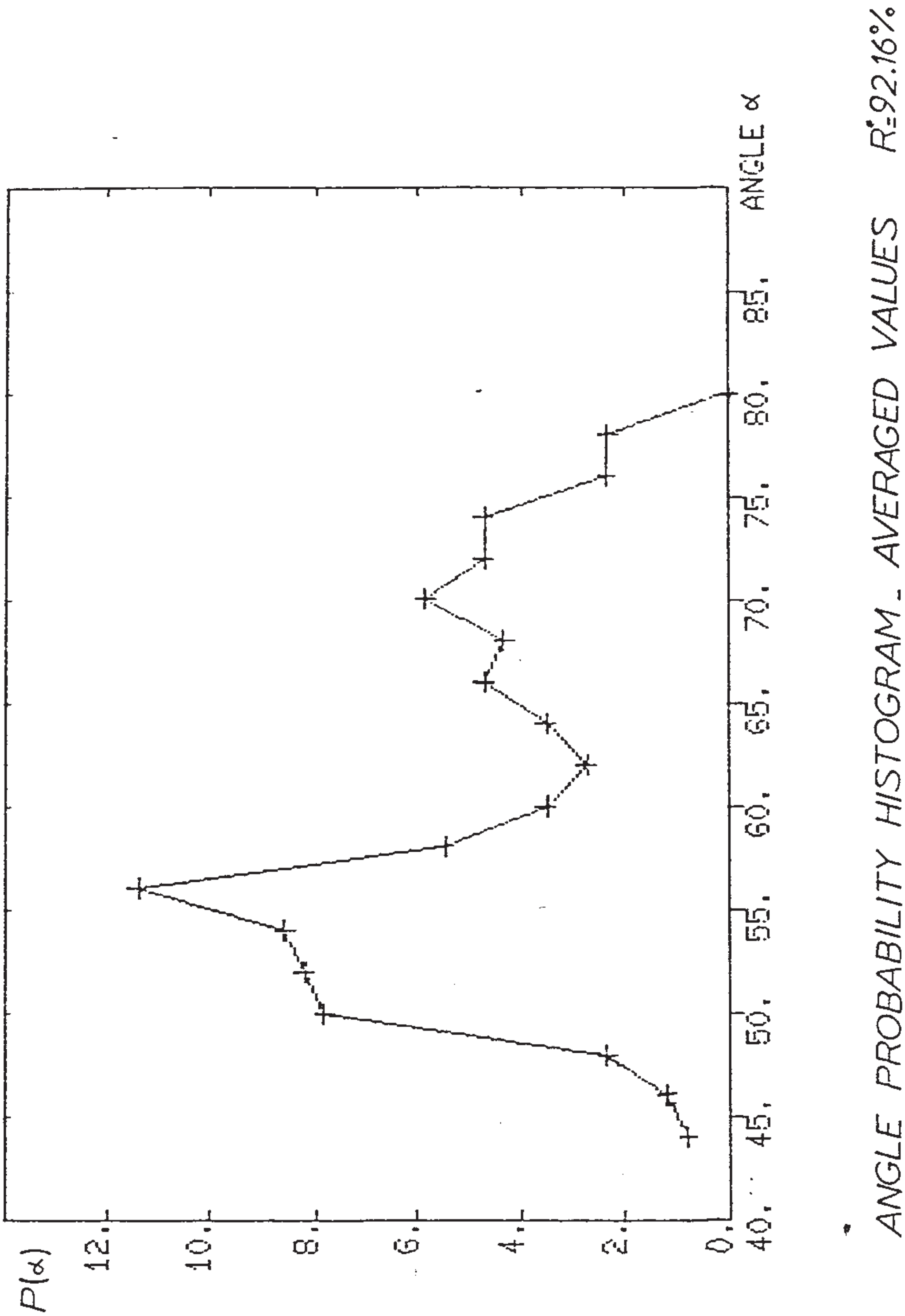

ANGLE PROBABILITY HISTOGRAM_ AVERAGED VALUES
R=92.16%
P(α)
ANGLE α
0.
2.
4.
6.
8.
10.
12.
40.
45.
50.
55.
60.
65.
70.
75.
80.
85.

Figure 18

AVERAGED VALUES

. Simplified Procedure

——————— "Inviscid" flow only

- - - - - - - Wake only

. Complete Procedure

—.—. "Inviscid" flow only

. Calculated Average

+ + + + + + $\bar{f} = \frac{\Sigma_i f_i N_i}{\Sigma_i N_i}$

Table 1