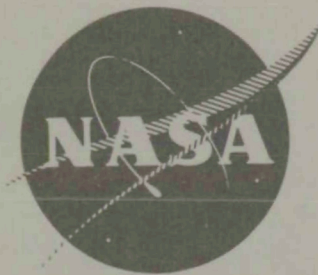


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SYSTEMATIC TWO-DIMENSIONAL CASCADE TESTS

VOL. 2 - MULTIPLE CIRCULAR-ARC HYDROFOILS

by

W. E. Taylor, T. A. Murrin and R. M. Colombo

UNITED AIRCRAFT RESEARCH LABORATORIES

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS3-4184

Werner R. Britsch, Project Manager

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CONTRACTOR REPORT

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East Hartford, Connecticut 06108

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NASA Lewis Research Center
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Werner R. Britsch, Project Manager
Liquid Rocket Technology Branch

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FOREWORD

The experimental investigation described herein was conducted by the Research Laboratories of the United Aircraft Corporation under Contract NAS3-4184 with the National Aeronautics and Space Administration. The work was performed under the management of the NASA Project Manager, Mr. Werner R. Britsch, Liquid Rocket Technology Branch, NASA Lewis Research Center. Technical direction was provided by Mr. L.J. Herrig, Special Projects Division, NASA Lewis Research Center.

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IV.

Report CR-72499

Systematic Two-Dimensional Cascade Tests

Vol. 2 - Multiple Circular-Arc Hydrofoils

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ABSTRACT

Performance parameters and cavitation indices are presented for cascades of hydrofoils with double (Vol. 1) and multiple (Vol. 2) circular-arc profile sections tested over a range of systematically introduced variables in a rectilinear cascade tunnel which uses water as the test medium. Cascade configurations included various combinations of an inlet flow angle ($\beta_{IN} = 60, 70$ and 75 deg), a cascade solidity ($\sigma = 0.75, 1.00$ and 1.50) and angles of incidence between positive and negative stall.

In Vol. 2, the incidence and deviation angles corresponding to the point of minimum total pressure loss coefficient were correlated, and the turning angles are presented in a form which makes it possible to determine the turning angles for arbitrary cascade configurations. The minimum loss incidence and deviation angles and the hydrofoil pressure distributions for multiple and double circular-arc hydrofoils are also presented for comparison.

SUMMARY

Performance parameters and cavitation indices were measured for cascades of two families of different circular-arc type profiles: one profile family was developed by superimposing a symmetrical double circular-arc base profile on various circular-arc mean camber lines; the second was developed by superimposing a symmetrical multiple circular-arc base profile on various NACA four-digit series meanlines. Cascade configurations included various combinations of an inlet flow angle ($\beta_{1N} = 60, 70$ and 75 deg), a cascade solidity ($\sigma = 0.75, 1.00$ and 1.50) and an incidence angle between positive and negative stall. For each configuration, measurements were obtained for presenting the following performance parameters as functions of incidence angle: total pressure loss coefficient ($\bar{w}$), turning angle (θ), deviation angle (δ°), diffusion factor (D), wake momentum thickness ratio (θ^*/s), cascade static pressure rise coefficient ($\Delta p/q_1$) and cavitation index (K). Results from cascade tests with a family of double circular-arc hydrofoils are reported in Vol. 1, and results from the cascade tests with a family of multiple circular-arc hydrofoils are reported in Vol. 2.

Volume 2, in addition to presenting the performance of seven different multiple circular-arc hydrofoils with systematically varied cascade geometries, presents surface pressure distributions for cascades of the 40-deg camber multiple circular-arc hydrofoils at various incidence angles. These cascades included an inlet flow angle of 60 deg and solidities of 0.75, 1.00 and 1.50. Pressure distributions for certain geometries of multiple and double circular-arc type hydrofoils are compared at incidence angles which are approximately the same distance from the incidence angle for minimum total pressure loss coefficient.

The incidence and deviation angles corresponding to the point of minimum total pressure loss coefficient were correlated; the turning angles are presented in a carpet plot from which the turning angles for arbitrary cascades may be derived.

INTRODUCTION

In order to meet future demands for high efficiency, low weight and improved cavitation characteristics in pumping equipment, continued refinement is required in the accuracy and range of applicability of both the experimental data and the analytical procedures which form the basis for modern pump design techniques. For many applications involving high flow rates, such as in large liquid fuel rocket engines, the above performance requirements are best satisfied by multi-stage axial-flow pumps. At the present time, one of the more successful techniques for the selection of blade geometries for the various radial stations in axial-flow machinery is based upon the application of data obtained from experiments using two-dimensional, rectilinear cascades of representative blade profiles.

A substantial amount of cascade data, compiled by a number of investigators in support of axial-flow compressor development, can be applied to pump design. However, these data are deficient in two important respects: 1) the inlet flow angle range to which the data apply does not include all conditions of interest in pump design, for example large inlet flow angles relative to the axial direction; 2) information relative to cavitation performance of the blade elements is not available.

A water tunnel was designed and erected at the United Aircraft Research Laboratories (UARL) in which cascade tests may be performed under cavitating and noncavitating conditions throughout a range of cascade variables. Under Contract NAS3-4184, with the National Aeronautics and Space Administration, certain modifications were made to the facility to increase the degree of control over the test section flow, and an experimental program was initiated to determine the two-dimensional turning and loss performance and the cavitation index of a series of circular-arc type hydrofoils when tested with various combinations of flow angles relative to the cascade inlet plane, flow angles relative to the blade mean line (incidence) and spacings between adjacent hydrofoils. The broad range of these test variables enabled the correlation of a design reference point and the presentation of the test data in the form of carpet plots which are useful for design evaluations.

ACKNOWLEDGMENTS

Recognition is extended to W. F. Perkins¹ for his many contributions to the design and operation of the water tunnel facility and to the analytical procedures required for machine computation of the test data; to K. L. Dauphinais² for writing and checking the machine program required for data reduction; to F. S. Owen³ for his technical and administrative guidance during the major period of the contract.

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TEST APPARATUS

UARL Cascade Water Tunnel

Basic Considerations

In a rectilinear cascade, a linear two-dimensional array of blades is used to simulate the blade geometry at a discrete radial location in a three-dimensional axial-flow machine. Measurements can then be obtained for determining the static pressure rise, total pressure loss coefficient and flow turning angle for this blade profile and blade spacing at various incidence angles. By testing cascades which simulate different radial stations, the flow characteristics through the blade rows in an axial-flow stage may be approximated by stacking the two-dimensional performance measurements of the blade elements.

A basic goal in the design of a cascade test section is to provide a flow in the cascade test apparatus which approximates the two-dimensional flow that would exist in an infinite array of blades having infinite span. This requires that means be provided in the test equipment to control wall boundary layer development and to contour the walls confining the flow so that the interference produced by the walls is minimized. Additional design specifications related to cascade performance testing are that the test apparatus have the flexibility to accommodate various cascade geometries and that the blade Reynolds number be greater than 2.5×10^5 to minimize the possibility of laminar separation from the blade surfaces.

In order to conduct cavitation tests under controlled conditions, the design of the flow circuit must be such that: 1) cavitation will occur on the test blades before it occurs on the circuit components; 2) the system will permit operation with test section pressures which are above and below atmospheric pressure, 3) contamination of the test medium by solid particles, dissolved ions and dissolved gases will be minimized, since these contaminants may become nuclei for premature formation of cavitation.

Facility Configuration

Over-all design of the water tunnel was largely dictated by the requirements for determining cascade cavitation coefficients and avoiding cavitation elsewhere in the test loop. The facility was therefore designed as a vertical, variable-pressure, closed loop arranged such that the main components of the test section are accessible from ground level. The test section is oriented such that the inlet plane of the cascade is

horizontal to eliminate hydrostatic pressure gradients along the length of the cascade, which would otherwise affect the uniformity of cavitation inception on the individual blades in the cascade. In order to provide sufficient net positive suction head at the pump inlets to prevent pump cavitation, the water circulating pumps are located at the lowest point in the test loop.

A drawing of the water tunnel is shown in Fig. 1. In this vertical flow circuit, the flow is discharged from the pumps, diffused and turned in a system of ducts and settled in a rectangular chamber containing both a honeycomb flow straightener and graded-porosity screens for reducing large scale turbulence. Subsequent guide vane sections provide the required flow alignment and a means for attachment between the settling chamber and interchangeable cascade inlet nozzles. The flow is first accelerated by the inlet nozzle, then passed through the cascade test section and finally discharged into a large plenum tank from which the flow completes the circuit to the circulating pumps.

The flow is accelerated to the prescribed velocity relative to the test section by means of one of the four interchangeable nozzles which were designed for inlet flow angles of 50, 60, 70 and 75 deg as measured relative to the axial direction, which is normal to the cascade inlet plane. (The 50-deg nozzle was not used during the program with the multiple circular-arc hydrofoils.) The design of the nozzles was greatly influenced by factors related to cavitation testing. The horizontal orientation of the cascade inlet plane required the nozzle to accelerate the flow downward to the cascade plane from the region of low static head which is present at the top of the inlet ducting. Therefore, the maximum vertical distance between the blade leading edge plane and the top of the inlet ducting was limited to the dynamic head at the test section. This insured lower static pressure at the cascade than at the top of the ducting, thereby minimizing the possibility of cavitation in this ducting. However, this dimension placed design restrictions on not only the maximum length available for the inlet nozzle but also the maximum height of the inlet cross section. The height, and a width which was restricted by the diameter of the plenum tank, limited the area contraction ratios of the relatively short inlets to 9.08, 11.4, 11.1 and 14.2 for the 50, 60, 70 and 75-deg nozzles, respectively. The contours for the nozzle walls were selected from an analysis of minimum length, two-dimensional contractions for accelerating flow (Ref. 1). Installation of the 60-deg inlet nozzle with the test section assembly is shown in Fig. 2.

The cascade test section assembly is supported from the fixed head of a 10-ft diameter plenum tank. The plenum tank has an operating pressure range between one and 100 psia as required for establishing the desired

cavitating or noncavitating test conditions and contains windows at the sides and top for observation of the test equipment or degree of cavitation during the tests. Enclosing the test section assembly within a removable pressure shell (plenum tank) affords the advantages of: 1) allowing complete accessibility of the test section when the plenum is open; 2) permitting relatively light-weight construction of the test section assembly, since immersion of the test section in the test fluid insures that the differential pressures on the test section walls are low throughout the operating pressure range of the tunnel; 3) minimizing the problem of air and water leakage in a test section which incorporates both interchangeable parts and variable geometry end walls and yet operates over a wide range of test pressures.

The three main flow pumps were fabricated from zinc-free bronzes and stainless steel. Each pump is driven by a 10 hp motor and is capable of delivering water flows at a rate of 1700 gpm with a head rise of 16 ft.

Contamination of the water used in the facility is minimized by special water processing equipment. In addition, the facility is constructed primarily of stainless steel to avoid solid particle shedding. Solid particles contained in the test medium are removed by various filters, one of which provides continuous three-micron filtration at a flow rate of 100 gpm. Dissolved minerals are removed from the test water by a commercial ion-exchange type demineralizer which provides water comparable to distilled water in conductivity, a measure of dissolved mineral content. The conductivity of the water from this unit was approximately 1 micromho centimeter. Dissolved gases may be removed by a cold-water deaerator which can reduce the gas content to three parts per million.

Cascade Test Section

The test section (Fig. 3) was designed to establish both a uniform flow along the cascade inlet plane and a periodic (blade-to-blade) flow downstream of the cascade. These are necessary conditions to insure that the flow about each blade is identical; accomplishment of these goals provides a flow which is representative of the flow through an infinite cascade. Approximations of flow uniformity and periodicity are achieved by removal of the wall boundary layers and by contouring the cascade end walls to minimize undesirable perturbation of the mainstream flow.

The boundary layer which develops along the walls of the inlet nozzle is removed upstream of the test section by means of step-type slots located on all four walls of the nozzle (Fig. 3). The boundary layer flow intercepted by each of the four step slots is ducted through individual throttling valves to a common pump. Within the test section,

porous side walls are used for removal of boundary layer flow in the immediate vicinity of the cascade as required for the simulation of two-dimensional flow through the cascade (Ref. 2). A porous wall assembly consists essentially of a rectangular plenum with an interchangeable porous metal wall which is fabricated from sintered woven wire mesh. A photograph of a porous sidewall assembly with the blades installed is presented in Fig. 4.

Perturbations of flow streamlines (to obtain uniformity) are accomplished by means of variable geometry end walls located at each end of the cascade as shown in Fig. 3. These end walls are comprised of three sections, a flexible wall which connects the rigid inlet nozzle end wall to an adjustable end wall, an adjustable end wall which is analogous to one surface of a cascade blade and a tailboard which extends downstream from the adjustable end wall. Actuation of these endwall sections enables independent adjustment of: (1) the gap between the end blades of the cascade and the adjustable end wall, (2) the angle of the adjustable end wall, (3) the angle of the tailboard. The convex, flexible end wall is porous (Fig. 3) to permit removal of the endwall boundary layer, thereby decreasing any tendency toward flow separation from this surface. Flow through the flexible porous wall and each porous side wall is independently controlled.

Blade aspect ratio and the number of blades to incorporate into a cascade assembly are selected somewhat arbitrarily. An aspect ratio of two was chosen as a compromise between the structural problem of blade bowing or bending that would be associated with high aspect ratio blades, and the undesirable three-dimensional flow effects that would occur with low aspect ratio blades. A compromise was also made between the large number of blades desired for simulation of the infinite cascade and the practical considerations of cost and test section size. Based upon general information obtained from previous experimental testing at UARL with a cascade tunnel which used air as the test medium and from the experimental evidence from NACA cascade tests (Ref. 3), it was decided to establish five blades as the minimum number to be included at the highest blade spacing (4 in.) considered in the current test program. These considerations, together with a specified minimum blade-chord Reynolds number of 5×10^5 and the selection of a 3-in. blade chord, established a minimum test section velocity of 22 ft per second. With a 5100 gpm facility pumping capability, the maximum cascade inlet flow area for each of the inlet flow angles was known. In order to remain within these limits, a test section of rectangular cross section having a 6-in. span with a 24-in. length was selected for the 60-deg inlet nozzle and a test section having a 6-in. span with a 36-in. length was selected for the 70 and 75-deg inlet nozzles.

The remaining considerations involved in selecting the test section configuration were primarily associated with the requirement that the facility accommodate configuration changes with relative ease. For this purpose, the design included interchangeable sidewall components, to simplify changes in the blade spacing, and remote actuators to permit adjustment of blade incidence angle, flexible endwall contour and tailboard angle without the need for opening the large plenum tank.

Hydrofoil Profiles

The multiple circular-arc (MCA) profiles are of the so-called "rear loading" type which have a larger proportion of their curvature near the trailing edge. The purpose of this profile shape is to provide a more uniform static pressure distribution along the forward region of the suction surface; consequently this profile shape should delay cavitation within this region on the hydrofoils.

Seven hydrofoil profiles, each with a maximum thickness-to-chord ratio of 0.06, were developed by superimposing the thickness distribution of a symmetrical base profile on NACA four-digit series camber lines (Ref. 4), which are described by the maximum camber location at the 60-percent chord station, and camber angles of 0, 10, 20, 25, 30, 40 and 45 deg. The profiles are described by the general family designation, NACA M606, where the letter (M) represents the maximum camber of the meanline as a percent of chord length, the digit (6) indicates the chordwise position of the maximum camber in tenths of chord length and the pair of digits (06) represents the maximum thickness of the basic profile in percent of chord length. The values for M corresponding to the given camber angles are presented in Table I and Fig. 5.

The fore and aft surfaces of the base profile were both formed by circular arcs. The circular arc forming the fore surface was tangent to the leading edge radius and had zero slope at the 60-percent chord station; the circular-arc forming the aft surface had zero slope at the 60-percent chord station and was tangent to the trailing edge radius. This thickness distribution placed the maximum thickness point at the 60-percent chord station. The seven profile sections are presented in Fig. 5, and the coordinates are presented in Table I. The 6-in. span, 3-in. chord hydrofoils were fabricated from stainless steel and then polished to a surface finish of 8 microinches (rms). The leading and trailing edge radii were 0.10 percent of the blade chord. As may be observed in Fig. 4, blade support shafts welded to both hydrofoil tips at the leading edge were used to support the hydrofoils firmly in the test section and also to permit remote adjustment of blade incidence angle.

Static pressure instrumentation was installed in two of the 40-deg camber hydrofoils for obtaining surface pressure distributions for a range of cascade variables. Twelve 0.020-in. diameter orifices were drilled into the suction surface of one hydrofoil and 12 also into the pressure surface of the other at the locations shown in Fig. 6. Local static pressures were led out from each hydrofoil blade by means of stainless steel tubing laid in grooves milled into the blade surface opposite the instrumented surface and along one of the stub shafts. After the tubing was installed, the grooves were filled with an epoxy cement and the surface was refinished to the original contour. Instrumented hydrofoils are shown in Fig. 7.

Instrumentation

The performance of a cascade of hydrofoils was determined from static and total pressure and flow directions measured both upstream and downstream of the cascade. Static pressures were measured by means of sidewall orifices which were spaced at one inch intervals along the length of the cascade. This arrangement of orifices provided an indication of the degree of uniformity of both the inlet and exit flows and therefore was useful for adjusting test section flow conditions as well as for indicating the cascade static pressure rise. Total pressures and flow angles were measured by means of two-dimensional, directional probes of the wedge and Kiel-wedge types as shown in Fig. 8; these probes provided a capability of measuring flow angle to an accuracy of $\pm 1/4$ deg. The designation "wedge" refers to the probe cross section at the pressure sensing location. The probes were traversed along the length of the cascade to within one gap from the end walls and could also be remotely positioned in the spanwise direction. The upstream probe and the upstream static pressure orifices were located in a plane which was 0.6 chord length (axially) upstream of the plane of leading edges. The axial position of the downstream probe traversing plane was varied so that the streamwise distance between the blade trailing edge plane and the probe was between one and two chord lengths for all cascade configurations.

An automatic data acquisition system (Fig. 9) was used to record cascade performance data by storing the data on paper tape. The tape-stored data were then processed by a high-speed digital computer. The data recorded from the upstream and downstream measurement stations included total pressure and flow angles, which were continuously acquired during traverses of the probes, and local static pressures which were acquired from the pressure orifices arranged along the length of the cascade. The pressures and flow angles were also visually displayed while testing using strip chart recorders for readout of probe traverse data

and both a multi-tube mercury manometer and an x-y plotter for indication of the individual wall static pressures.

Each of the inlet flow nozzles was provided with a window in the upper wall, aligned with the window at the top of the plenum tank, through which the central portion of the cascade could be observed and photographed during cavitation tests. For visual detection of cavitation, the test section was illuminated from strobe lights which also provided the short duration, high intensity illumination required for cavitation photographs.

PROCEDURES

Test Program

The test program was established to determine, experimentally, the performance of cascades of multiple circular-arc profiles when operated over a range of incidence angles with various inlet flow angles and cascade solidities. Incidence angle is defined as the difference between the inlet flow angle and the angle of the tangent to the profile mean line at the leading edge. For these multiple circular-arc profiles (NACA M606), the incidence angle (i) is related to angle-of-attack (α), which is a reference angle used by many investigators (e.g., Ref. 2 and 3) through the expression

$$i = \alpha - \Delta$$

The value of Δ for each profile is presented in Table I.

The broad range of test variables included in this investigation enables the correlation of these experimental data throughout regions of interest to both axial-flow pump and compressor designers. The test configurations, which consisted of various combinations of inlet flow angles ($\beta_{1N} = 60, 70$ and 75 deg) and cascade solidities ($\sigma = 0.75, 1.00$ and 1.50) with the multiple circular-arc profiles shown in Fig. 5, are presented in Table II. The 60 -deg inlet flow angle is in the range of cascade tests which had been conducted by other investigators for the development of axial-flow compressors and therefore provides a means for comparing and correlating these water cascade data with cascade data obtained from other test programs wherein air was used as the test medium. The data from tests with the 70 and 75 -deg inlet flow angles are in the range of interest for pump design and are also of importance for extrapolating the correlations of compressor cascade data to these higher inlet flow angles.

Each of the cascade configurations, represented by a particular profile shape, inlet flow angle and cascade solidity, was tested over an incidence angle range which included the points of positive and negative stall, where stall is defined as the point at which the total pressure loss coefficient is double the minimum value.

Test Procedure

The test procedure for each set of cascade hydrofoils involved extensive iterative adjustments of the various flow control devices to achieve the best approximation to the desired two-dimensional flow in the cascade. At the start of this procedure, the hydrofoils were set at an angle estimated to be close to the incidence angle corresponding to the point of blade minimum total pressure loss coefficient. The flow velocity was then adjusted to provide a Reynolds number (Re_c), based upon the chord length, of approximately 5×10^5 . The results from various cascade tests (e.g., Refs. 2 and 3) indicated that this value of Re_c was well above the critical Reynolds number range. Therefore, extensive laminar separation from the hydrofoil surfaces was unlikely, and the effects of Reynolds number on the cascade performance parameters was expected to be minor. The endwall geometries and boundary layer control flow rates were then progressively adjusted to produce uniform distributions of inlet and exit wall static pressures and essentially constant inlet flow angles along the full length of the cascade.

After a relatively uniform inlet flow distribution was obtained (inlet flow angle constant to within ± 0.8 deg of the value at the center of the cascade), the distributions of exit flow angle and total pressure were examined in the same manner; the porous endwall flow rate and tailboard settings were adjusted accordingly to improve periodicity of the exit flow. A calculation was then made to determine if the dynamic pressure ratio across the cascade was within ± 0.05 of the value computed from an approximation of the two-dimensional continuity equation which is defined by:

$$\left(\frac{q_2}{q_1}\right)_{2D} = \left[\frac{1}{2} \left(\frac{\cos \beta_1}{\cos \beta_2} + \sqrt{\left(\frac{\cos \beta_1}{\cos \beta_2}\right)^2 + 2\bar{\omega}} \right) \right]^2 \quad (1)$$

where:

$$\bar{\omega} = \frac{1}{s} \int_0^s \frac{\Delta P}{q_1} dy \quad (2)$$

These terms are defined in Appendix I.

Equation (1) was used to estimate the adjustments required to control the sidewall boundary layer thickness, thereby eliminating spanwise divergence or convergence of the streamlines and producing effective two-dimensional flow. If required, an appropriate change in sidewall flow removal rate was made, and the inlet flow was resurveyed since changes in blade loading affect the inlet flow field. An iterative procedure for evaluating and modifying upstream and downstream flow fields was thus established. A minimum of three complete iteration cycles was required for the first test of a cascade configuration before both upstream and downstream flow fields were acceptably uniform or before it had become obvious that significant improvements in flow uniformity could not be obtained. The time required for the iteration procedure varied from a minimum of approximately three hours to a maximum of about eight hours.

After obtaining the data for an initial test point of a configuration, subsequent test points were established by changing the blade-chord angle in approximately 2-deg increments until an incidence angle range was covered which included minimum loss incidence angle and values of incidence angle corresponding to twice the minimum total pressure loss coefficient. Each additional test point required an iterative procedure of flow adjustment identical to that described for the initial test point except that only one iteration was generally required. Approximately two hours were required to establish the flow uniformity and obtain the data for each additional test point.

A great variation in flow removal was required for cascade boundary layer control throughout the extremes of incidence angle between positive and negative stall. During tests of highly cambered hydrofoils at incidence angles approaching positive stall, the porous wall boundary layer control system was required to remove a substantial portion of the main stream flow to achieve two-dimensional flow conditions. Under conditions of severe separation or in the range of the highest static pressure ratios, the two-dimensional condition could not always be achieved even though maximum flow was being removed by the porous wall boundary layer control system.

During tests of low-cambered hydrofoils at incidence angles approaching negative stall, the boundary layer control system was required to remove only a small portion of the mainstream flow to achieve two-dimensionality. For some low static pressure ratio conditions, two-dimensionality was often achieved without the use of the porous wall boundary layer control system. Extreme low static pressure ratio conditions were encountered for which it was impossible to achieve two-dimensional flow even though this boundary layer control system was not utilized.

Although some of the test conditions near positive and negative stall incidence were not two-dimensional as defined, test points were obtained in this region in order to provide data which may be useful for achieving a reasonably meaningful extrapolation of the two-dimensional data. Some of the data in the low loss regions are also reported as being non two-dimensional. However, these test points were determined to be two-dimensional within the required limits through a comparison of experimental and theoretical values of the q_2/q_1 ratios which were computed by hand at the time the tests were being conducted. Subsequent computer computations using the tape-stored data resulted in a difference between the experimental and theoretical values of q_2/q_1 which slightly exceeded the allowable value of ± 0.05 . Nonetheless, these values are reported as non two-dimensional data. It should be noted that even the indicated non two-dimensional data points near stall were generally within a few percentage points of being classified "two-dimensional" as defined in this report.

Before conducting cavitation tests, the water was deaerated for a minimum of six hours either by using the deaerator system or by reducing the pressure in the plenum tank. The cavitation index was determined from the point of cavitation desinence by first reducing the test section pressure until fully developed cavitation was established along the cascade and then gradually increasing the pressure until the cavitation disappeared (cavitation desinence). At this point the absolute pressure, dynamic pressure and temperature in the free stream were recorded for calculation of the cavitation index. A minimum of two hours was required for the cavitation measurements.

Data Reduction Procedure

The measurements of cascade static pressures, total pressures and flow angles were stored on paper tape by the data acquisition system (Fig. 9) and were later converted to cascade performance parameters by a computer program. This program computed and tabulated the flow angle and wall static pressure distributions along the entire cascade and also the hydrofoil wake parameters for each wake traversed. The equations and methods used in calculating the cascade performance parameters are outlined in Appendix I; the significance of the various terms in these expressions may be determined by reference to Fig. 10 which is a schematic presentation of the cascade nomenclature.

The computed distributions of pressure and flow angle were then examined to determine the uniformity and periodicity of the flow for the particular test configuration. In addition, the pressure and flow angle distributions over the two central gaps of the cascade were averaged to give representative values for inlet and exit flow angles, total pressure loss coefficient,

momentum thickness ratio and inlet and exit static pressures. The diffusion factors and deviation angles for each cascade were determined from the averaged inlet and exit flow angles.

The nondimensional cavitation index, K , was calculated from the inlet static pressure (p_1) at which cavitation had just disappeared from the hydrofoil surfaces and the vapor pressure of the water (p_v) at the test temperature using the expression,

$$K = \frac{p_1 - p_v}{q_1} \quad (3)$$

PRESENTATION OF RESULTS

For each of the test configurations, the characteristics of the performance parameters ($\bar{a}$, θ , D , θ^*/s , $\Delta p/q_1$, K) are presented as functions of incidence angle in Figs. 11 through 49; the order of presentation is shown in Table II. Since the average inlet flow angles (β_1) as determined from flow surveys at the upstream measuring station were often slightly different from the fixed inlet nozzle angles (β_{1N}), these average inlet flow angles are also presented for each test point in Figs. 11 through 49. Prior to fairing curves through the parameter test points, the data were cross plotted and compared for the purpose of evaluating trends and disclosing possible experimental errors; corrections were made in accordance with the results obtained from checking the data or, when necessary, by repeating a test point. By means of these smoothing processes, curves were developed and presented which reflect greater precision in the numerical values of the performance than could be achieved by simply fairing the curves through the actual test points. However, because of this procedure, the faired curves do not necessarily pass through the plotted data points.

Static pressure distributions for the 40-deg camber hydrofoil in cascades with an inlet flow angle of 60 deg and solidities of 0.75, 1.00 and 1.50 are presented in Fig. 50. Data are presented for incidence angles near the point of minimum total pressure loss coefficient and also for incidence angles near positive and negative stall.

A convenient reference point which may be used as the basis for developing empirical cascade performance prediction systems is the incidence angle at which the minimum value of total pressure loss coefficient occurs. Using the minimum total pressure loss coefficient as a reference, these test data were correlated in a manner similar to that which was used for determining the correlation presented in Ref. 5. For the correlation of the multiple circular-arc hydrofoil data, the variable, minimum loss incidence (or deviation) angle, for a given cascade configuration is assumed to be a linear function of the minimum loss incidence (or deviation) angle for the zero degree camber hydrofoil and a correction term related to the camber angle. In equation form, these reference angles may be expressed as

$$i = i_{\bullet} + n \phi$$

and

$$\delta^{\circ} = \delta_{\bullet}^{\circ} + m \phi$$

where $i_{\bullet}$ and $\delta_{\bullet}^{\circ}$ are the values for the zero camber hydrofoil and n and m are the respective rates of change of incidence and deviation with camber angle.

The minimum loss incidence angles for zero degree camber hydrofoils ($i_{\bullet}$) and the slope factors (n) are presented as functions of inlet angle in Figs. 51 and 52, respectively; the minimum loss deviation angles for zero degree camber hydrofoils ($\delta_{\bullet}^{\circ}$) and slope factors (m) are presented as functions of inlet flow angle in Figs. 53 and 54, respectively. Reference minimum loss incidence and deviation obtained from the correlation and from curves faired through the test data are presented as functions of camber angle in Fig. 55.

The turning angle data are correlated in the form of carpet plots (Ref. 6) in Fig. 56 to facilitate the interpolation of turning angles for arbitrary cascades of these multiple circular-arc hydrofoils within the range of the test variables. For convenience, the carpet plot is presented as a separate enclosure contained within the back cover of the report.

Pressure distributions for cascades of 40-deg camber, multiple and double circular-arc hydrofoils with an inlet flow angle of 60 deg and solidities of 0.75, 1.00 and 1.50 are presented for comparison in Fig. 57.

The data presented represent incidence angles at approximately the same distance from the incidence angle for minimum total pressure loss coefficient; two different blade operating conditions are presented for each solidity.

DISCUSSION

Cascade Performance

The performance parameters, $\bar{w}$, D , θ^*/s , $\Delta p/q_1$ and K , of these hydrofoils in cascades vary in a systematic manner with changes in both cascade geometry (β_1 , 1 , σ) and hydrofoil profile shape (as specified by the camber angle). Some of the characteristics which may be observed for the test parameters are discussed briefly in the following sections.

Total Pressure Loss Coefficient

The variations of total pressure loss coefficient with incidence angle are represented by "bucket" shaped curves, similar to those which characterize the loss data obtained from cascades using air as the test medium. These loss curves serve as one basis for comparing the relative performance of various hydrofoil (or airfoil) profiles. The standards from which relative performance may be determined from these curves are the incidence angle at which minimum total pressure loss coefficient occurs, the minimum value of total pressure loss coefficient and the range of incidence angle between arbitrarily established high values of total pressure loss coefficient, usually associated with the incidence angles at which positive and negative stall occur. An optimum profile in cascade would provide the lowest total pressure loss and the widest operating range within the established limits.

Minimum values of total pressure loss coefficient are affected by inlet flow angle, camber angle and solidity. The minimum values of loss coefficient are not as important to the designer as the incidence angle at which minimum loss occurs or the shape of the loss curve since the blading for high performance turbomachines would generally be designed for blade element operation at incidence angles which provide a required turning of the flow rather than for a particular value of minimum loss. The minimum total pressure loss coefficient is useful for defining an operating range or stall limits for cascades; as defined herein, the stall limits are the incidence angles where the total pressure loss coefficient is twice the minimum value. Within the stall limits, operating ranges for the MCA (NACA M606) hydrofoils are between 6 deg (Fig. 38a)

and 12 deg (extrapolated) (Fig. 11a). The operating ranges are generally small because of the sharp leading edges (0.003 in. radius) which probably precipitated boundary layer transition from a point near the leading edge as the incidence angle was varied from minimum loss incidence. The resulting increased boundary layer thicknesses near the trailing edge caused early flow separation as the incidence angle was varied.

Turning Angle

Turning angles for the 0 and 10-deg camber hydrofoils increased linearly with increasing incidence angle, and the slopes of the turning angle curves increased with increasing solidity. For camber angles of 20 deg and above, the turning angles also increased linearly with incidence angle, but a point was usually reached where the slopes of the curves decreased. At an incidence angle a few degrees greater than that where the slope of the turning angle curve decreased, turning was observed to increase again (Fig. 18a) or decrease (Fig. 21a), a characteristic which appears to be a function of camber angle. For those configurations where turning is observed to decrease within a range of increasing incidence angles, a continuation of the configuration tests to higher incidence angles generally resulted in correspondingly higher turning angles; this effect was prevalent for the high solidity ($\sigma = 1.50$) tests as may be observed in Figs. 19a, 22a and 25a. An apparent exception was the configuration of $\beta_{1N} = 75$, $\sigma = 1.50$, $\phi = 25$ (Fig. 49a) where the turning angles are indicated to decrease as the highest incidence angle of these tests was approached. These data are unreliable, however, because the flow surveys at the highest incidence angles indicated no wake-free regions between adjacent hydrofoils; therefore, the test points were not "two-dimensional" as defined herein. A comparison of the characteristics data indicate that the slopes of the turning angle curves, for fixed inlet flow angle and solidity, are independent of camber angle except for the highest camber angles tested, where the slopes are higher.

Diffusion Factor

Since the diffusion factor of Ref. 7 and as defined in Appendix I is a function of the flow angles upstream and downstream of the cascade, the shape of a diffusion factor curve may be expected to resemble that of the turning angle curve for a corresponding cascade configuration; this trend is evident in Figs. 11b through 49b. A purpose of the diffusion factor is to establish loading limits for cascades; 0.60 has been established in Ref. 5 as the value of diffusion factor above which losses may be expected to increase very rapidly. Some of the cascades tested for this program achieved diffusion factors between 0.50 and 0.60 in the low loss region of their operating ranges, but none of the cascades achieved diffusion factors

greater than 0.60 in this range. Therefore, a load-limiting diffusion factor cannot be substantiated for these hydrofoils from the results presented.

Wake Momentum Thickness Ratio

For a given cascade configuration, variations in the incidence angle cause the ratio of wake momentum thickness to blade spacing to behave in a manner similar to the variation in total pressure loss coefficient with incidence angle. The minimum value of momentum thickness ratio also tends to increase with increasing camber, solidity and inlet flow angle, a characteristic which is also evident for minimum pressure loss coefficient. Due to the absence of wake-free regions between adjacent hydrofoils for the configuration of $\beta_{1N} = 75$, $\sigma = 1.50$, $\phi = 25$, no wake momentum thickness ratio data are presented in Fig. 49b.

Static Pressure Rise Coefficient

The static pressure increase across a cascade is influenced by both the cascade turning angle and the total pressure losses which are manifested in the wakes from the cascade blading. An additional effect on static pressure rise will result from the sidewall boundary layer growth through the cascade if the cascade flow is not two-dimensional. It should be expected therefore that the static pressure rise curves would exhibit incidence angle effects generally similar to those observed for the cascade turning angles. The curves of static pressure rise coefficient, presented in Figs. 11 through 49, do indicate increasing static pressure rise coefficient with increasing incidence angle but do not always indicate a characteristic similar to that exhibited by the turning angle curves at high incidence angles, that is, an increase in the slope of the curve at incidence angles above positive stall. A continued increase in static pressure rise would not be expected for this condition because the large wakes from badly stalled blades would diminish the wake-free region and therefore prevent deceleration of the discharge flow immediately downstream of the cascade.

The maximum static pressure rise coefficient achieved during this test program was 0.60. This was achieved with the 20, 25 and 30-deg camber hydrofoils in cascades with an inlet flow angle of 70 deg and a solidity of 1.50 (Figs. 31a, 34a and 37a, respectively) and was approximately achieved with the 40 and 45-deg camber hydrofoils with an inlet flow angle of 60 deg and a solidity of 1.50 (Figs. 22a and 25a, respectively) and the 20 and 25-deg hydrofoils with an inlet flow angle of 75 deg and a solidity of 1.50 (Figs. 46a and 49a, respectively).

Hydrofoil Pressure Distributions

The hydrofoil static pressure distributions, presented for a range of incidence angles for the 40-deg camber hydrofoils installed at solidities of 0.75, 1.00 and 1.50 with the 60-deg inlet nozzle, show that the pressures on the suction surface increased with increasing solidity for all incidence angles. Separation from the suction surface is indicated at the highest incidence angles for each solidity. The point of minimum pressure on the suction surface was no further forward than the 40-percent chord station for any configurations except for incidence angles greater than -2.3 deg at $\sigma = 1.50$; there were no steep pressure gradients along the suction surface for any of the test configurations.

Cavitation Index

The cavitation indices presented represent the highest pressures at which cavitation could be observed on the hydrofoils. The low operating pressure required to introduce cavitation on the hydrofoil surfaces also resulted in the formation of cavitation within the boundary layer control systems, reducing their effectiveness in maintaining two-dimensional flows. For this condition, the inlet flow distributions were often non-uniform, with the result that cavitation was most prevalent from both the surface of the porous, flexible, convex end wall and the adjacent hydrofoil. However, cavitation did appear uniformly on the hydrofoils further from the porous, flexible, convex end wall, therefore the cavitation indices were obtained from observations along the surfaces of these hydrofoils.

Because of the porous side wall boundary layer control system, it was possible to view cavitation only from above or below the cascade and this created some special problems. Adequate illumination and viewing could not always be achieved for the cavitation studies, especially when testing the highly cambered hydrofoils at a solidity of 1.50. The more difficult problem was that of attempting to determine cavitation desinence on the pressure surfaces of hydrofoils while observing through the cavitation bubbles swept from the porous end wall and the leading adjacent blade in the cascade. This uncertainty of the presence of cavitation made impractical the measurement of cavitation from the pressure surfaces of the hydrofoils, and the results presented therefore represent only suction surface cavitation.

During the preliminary cavitation tests, the cavitation index was determined in two ways: 1) by decreasing the pressure until cavitation on the hydrofoils was first observed, the point of incident or incipient cavitation; 2) by decreasing the pressure until cavitation was well

developed and then slowly increasing the pressure until cavitation was no longer evident on the hydrofoils, the point of desinent cavitation. These tests indicated that the cavitation index was the same whether obtained from incipience or desinence. The point of desinent cavitation was more easily detected, therefore the cavitation indices presented were determined from cavitation desinence rather than incidence.

When testing the low camber hydrofoils, cavitation in the nozzle or from the suction slots of the primary boundary layer control system was often detected before cavitation was observed along the hydrofoil surfaces. When these conditions occurred, the test data were invalid and additional tests were conducted at higher incidence angles where cavitation occurred at higher pressures in an attempt to generate curves of cavitation test data for the hydrofoils.

DATA CORRELATION AND COMPARISON

Minimum Loss

The incidence and the corresponding deviation angles at which minimum loss occurred are presented in Fig. 55 as functions of camber angle and solidity. The plotted values were obtained from the faired curves presented in Figs. 11 through 49. These data for cascades with 60 and 70-deg inlet flow angles show a linear progression toward lower minimum loss incidence angle and higher deviation angles with increasing camber angle. However, the data for cascades with the 75-deg inlet flow angle and a solidity of 1.50 indicate a limiting camber angle of approximately 20 deg beyond which the camber effect on the minimum loss incidence is not linear. However, the test points for this cascade configuration were not two-dimensional, therefore the accuracy of the turning angle data for this test point is questionable.

The curves presented in Fig. 55 were derived from the correlation curves (Figs. 51 through 54) and indicate for a wide range of camber angles the same linear variation in minimum loss incidence and deviation with camber as is indicated by the interpretation of test data. There is an indication that these curves may not be linear at the highest camber angles, therefore one should exercise caution in attempting to extrapolate the correlation much beyond the included range of test variables.

Incidence angles and turning angles for minimum loss, obtained from tests of double circular-arc (DCA) hydrofoils, are also presented in Fig. 55 to provide a comparison of the performance of multiple and double circular-arc hydrofoils in cascades. This comparison of multiple and

double circular-arc hydrofoil data shows that the rate of change of minimum loss incidence angle with camber is less for the multiple circular-arc hydrofoils and the rate of change of minimum loss deviation angle with camber is greater for the multiple circular-arc hydrofoil.

Pressure Distributions

Some of the pressure distributions obtained from testing cascades of 40-deg camber multiple (MCA) and double (DCA) circular-arc hydrofoils with an inlet flow angle of 60 deg and solidities of 0.75, 1.00 and 1.50 are presented in Fig. 57. These data, obtained from Fig. 50 of this report and from Fig. 111 of Ref. 8, show the blade loading distributions obtained with two different circular-arc type profiles, both of which were designed to provide a relatively uniform loading distribution for a range of incidence angles. Figure 57 was prepared in a manner which directly compares the pressure distributions for incidence angles which are approximately equidistant from the incidence angle for minimum total pressure loss coefficient, in addition, since the turning angles represented by these conditions generally differed by less than 3 deg, the figure also illustrates the pressure distributions for very similar blade loadings of the two profiles.

At a solidity of 0.75 (Fig. 57a), the pressure distributions show lower suction surface pressures for the double circular-arc hydrofoil up to the 60 percent chord station. The minimum pressure for the DCA hydrofoil occurred at the 45 and 50 percent chord locations for incidence angles of -11 and -13 deg, respectively. Minimum pressure occurred near the 60 percent chord location for both incidence angles presented for the MCA hydrofoil at $\sigma = 0.75$. Immediately downstream of the leading edge, neither hydrofoil exhibited a sharply peaked pressure distribution for the incidence angles presented.

At a solidity of 1.00 the pressure distributions show lower suction surface pressure for the double circular-arc hydrofoil between the 15 and 50 percent chord stations. Minimum pressure for the double circular-arc hydrofoil occurred at the 30 percent chord station for an incidence angle of -6 deg and at the 40 percent station for an incidence angle of -10 deg. Minimum pressure for the multiple circular-arc hydrofoil occurred near the 50 percent chord station for both incidence angles.

For a solidity of 1.50 the double circular-arc hydrofoil had lower suction surface pressures between the 10 and 50 percent chord stations at $i = -3$ and also between the 10 and 75 percent chord stations at $i = -8$. Minimum suction surface pressures occurred at the 20 percent chord station on the DCA hydrofoil for an incidence angle of -3 deg and at the 35 percent

chord station for an incidence angle of -8 deg. Minimum suction surface pressure occurred near the 40 percent chord station on the MCA hydrofoil for an incidence angle of -4.3 deg.

As would be expected, the MCA hydrofoils display pressure distributions along the suction surface, for these comparable incidence angles, which are flatter than those for the DCA hydrofoil and locations of minimum pressure which are closer to the trailing edge. However, as indicated by the areas within the pressure distribution curves, the DCA hydrofoil exhibited greater lift for each of the conditions presented.

Carpet Plot

The cascade data are summarized using a carpet plotting technique (Ref. 6). This technique presents a function of several independent variables on a single two-dimensional graph. This graphic presentation facilitates the selection of a blade camber angle and angle-of-attack which will provide the turning angle specified by a design velocity vector diagram. Within the range of the test parameters, the carpet plot which is presented in Fig. 56 may be used to predict the turning angle and angle-of-attack for arbitrary cascade geometries which incorporate various combinations of camber angle, inlet flow angle and solidity. The carpet plotted data comprise a range of camber angles from 0 to 45 deg, inlet flow angles of 60, 70 and 75 deg and solidities of 0.75, 1.00 and 1.50.

This plotting technique features an abscissa scale with a shifting origin. The origin is shifted in the x direction by an amount proportional to the increment of the variable represented. In this case, each carpet plot is separated from the next by a number of units proportional to the difference in camber (4 units equal one deg of camber). In order to avoid overlapping of the carpets, the ordinate scale is shifted vertically a number of units proportional to the solidity. For solidities of 0.75 and above, the turning angle (θ) is obtained from the following expression:

$$\theta = R - 48(\sigma - 0.75) \quad (4)$$

where R is the actual ordinate scale on the carpet plot.

Each of the individual plots on Fig. 56 presents turning angle, angle-of-attack and inlet flow angle for a prescribed solidity and camber angle. For a given solidity, similar carpet plots, or a portion of a carpet plot, may be constructed for intermediate camber angles by linear interpolation between corresponding values of α and β_1 on the given carpet plots for higher and lower camber angles. The individual carpet plots, representing increasing camber angle, were separated such that four units in the horizontal direction represent one degree of camber.

In a similar manner, individual carpet plots, or a portion of a carpet plot, may be constructed for an intermediate solidity by linear interpolation between corresponding values of α and β_1 on carpet plots which differ in solidity but have the same camber angle. A double interpolation is required for constructing a carpet plot to represent an intermediate camber angle and solidity.

CONCLUDING REMARKS

A family of multiple circular-arc hydrofoils, which were developed on NACA four-digit series mean lines, were tested with combinations of three different inlet flow angles and three different solidities. These tests provided a broad base of experimental data which have been correlated in a form which makes the data useful for axial-flow turbomachinery design evaluations.

The test results indicate that these multiple circular-arc hydrofoils operate with essentially "peak-free" pressure distributions along the suction surface throughout the included operating ranges; the suction surface pressures along the forward section of the hydrofoil are generally higher (less negative) than those for comparably cambered double circular-arc hydrofoils.

It should be recognized that the correlation presented herein was developed from systematic cascade tests with fixed inlet flow angles. Therefore, the values of minimum total pressure loss coefficient and the incidence angle at minimum total pressure loss coefficient may not be identical to those which would be determined from cascade tests with fixed blade-chord angles and a varying inlet flow angle as was pointed out in Ref. 5. No allowance was made for this difference because: 1) there were no available sources of systematic multiple circular-arc data available for establishing this difference, if it does exist for the MCA hydrofoil, and 2) the increments in inlet flow angle for the

systematic tests reported herein, 5 and 10 deg, were too great to permit an accurate determination of the minimum loss incidence for fixed blade chord angle from these data.

Several attempts were made to correlate the cavitation data. Although general levels of the cavitation indices for fixed inlet flow angle and solidity were evident, the cavitation indices for hydrofoils with different camber angles did not vary in a systematic manner; therefore, the correlation results were not entirely satisfactory. Review of the cavitation data indicated an effect of inlet flow angle (cavitation indices for the 60 deg inlet tests were lower than those for the 70 and 75 deg inlet tests) but the trend for this effect could not be established. Comparison of cavitation data from the multiple and circular-arc (Ref. 8) hydrofoil tests did not reveal a consistent trend in cavitation index between the two hydrofoil families nor did this comparison enhance the possibility of a correlation of the cavitation data with cascade parameters. The most consistent patterns of cavitation data were obtained from the 60 deg inlet tests at solidities of 0.75 and 1.00.

APPENDIX I

Equations for Data Reduction

For the acquisition of data, the test procedures were established to: (1) exclude turning angle measurements within the wake regions, (2) measure flow angles and total pressures only at the midspan position, and (3) adjust the flow conditions to provide effective two-dimensional flow through the cascade. An expression based upon the continuity equation was derived for determining the two-dimensional dynamic pressure ratio to provide a reference for estimating the two-dimensionality of the test data. This expression,

$$\left(\frac{q_2}{q_1}\right)_{2D} = \left[\frac{1}{2} \left(\frac{\cos \beta_1}{\cos \beta_2} + \sqrt{\left(\frac{\cos \beta_1}{\cos \beta_2}\right)^2 + 2\bar{\omega}} \right) \right]^2 \quad (1)$$

is an approximation to the two-dimensional continuity equation in which the integrations are performed for a sine-squared variation of total pressure and a sine variation of angle across a blade wake. This approximation, which includes wake blockage effects on the exit flow area, is valid within experimental error if (1) the total pressure loss coefficient, $\bar{\omega}$, is less than 0.10, (2) the flow angle variations from the mean exit flow angle are less than 15 deg, and (3) the width of the wakes at the measuring station are less than the blade spacing. This expression was derived using the methods prescribed in Ref. 2. Effective two-dimensional flow was assumed when the average experimental dynamic pressure ratio was within ± 0.05 of the value computed by the above expression using the average measured exit flow angle.

The total pressure loss coefficient, $\bar{\omega}$, is the nondimensionalized total pressure loss across a blade wake averaged across the blade spacing and is expressed by the formula

$$\bar{\omega} = \frac{1}{s} \int_0^s \frac{P_1 - P_2}{q_1} dy \quad (2)$$

The experimental dynamic pressure ratio is expressed as

$$\left(\frac{q_2}{q_1}\right)_E = \frac{P_1 - p_2}{P_1 - p_1} \quad (3)$$

APPENDIX I
(Contd.)

An expression developed in Ref. 9 to relate the total pressure loss coefficient to the wake momentum thickness (θ^*) and wake shape factor (H) at the downstream measuring station is given by

$$\bar{\omega} = 2 \left(\frac{\theta^*}{c} \right)_2 \frac{\sigma}{\cos \beta_2} \left(\frac{\cos \beta_1}{\cos \beta_2} \right)^2 \left\{ \frac{\frac{2H_2}{3H_2-1}}{\left[1 - \left(\frac{\theta^*}{c} \right)_2 \frac{\sigma H_2}{\cos \beta_2} \right]^3} \right\} \quad (4)$$

which indicates the contributions by the cascade geometry terms: σ , β_1 , β_2 , and the aerodynamic terms: θ^* , H (the contribution of the expression within the braces was stated in Ref. 9 to be very small). For the presentation of cascade characteristics, the momentum thickness is ratioed to the blade spacing and the total pressure loss coefficient expression is given by

$$\bar{\omega} = \frac{2}{\cos \beta_2} \left(\frac{\theta^*}{s} \right)_2 \left(\frac{\cos \beta_1}{\cos \beta_2} \right)^2 \left\{ \frac{\frac{2H_2}{3H_2-1}}{\left[1 - \left(\frac{\theta^*}{s} \right)_2 \frac{H_2}{\cos \beta_2} \right]^3} \right\} \quad (5)$$

The momentum thickness ratio was calculated from the expression

$$\frac{\theta^*}{s} = \frac{1}{s} \int_{\delta_{ly}}^{\delta_{uy}} \left(1 - \frac{v}{v_0} \right) \frac{v}{v_0} dy \quad (6)$$

where the limits of integration are the wake boundaries. This expression, by inclusion of the Bernoulli equation, becomes

$$\frac{\theta^*}{s} = \frac{1}{s} \int_{\delta_{ly}}^{\delta_{uy}} \left[\sqrt{1 - \frac{\Delta P}{q_2}} - \left(1 - \frac{\Delta P}{q_2} \right) \right] dy \quad (7)$$

APPENDIX I
(Concluded)

In Ref. 5, it was stated that a factor to be used for wake thickness correlations is the diffusion of blade surface velocities because of the contribution of this diffusion to the wake shape. A diffusion factor (D) developed in Ref. 7 is expressed for incompressible flow as

$$D = \left(1 - \frac{\cos \beta_1}{\cos \beta_2} \right) + \frac{\cos \beta_1}{2\sigma} (\tan \beta_1 - \tan \beta_2) \quad (8)$$

The significance of this diffusion factor is restricted to the region of minimum loss.

APPENDIX II

List of Symbols

A	Flow area, sq in.
c	Hydrofoil chord length, in.
C_P	Pressure coefficient, $\frac{p_{local} - p_i}{p_i - p_i}$
D	Diffusion factor, $\left(1 - \frac{\cos \beta_1}{\cos \beta_2}\right) + \frac{\cos \beta_1}{2\sigma} (\tan \beta_1 - \tan \beta_2)$
H	Boundary layer form factor, δ^*/θ^*
i	Incidence angle, angle between inlet-flow direction and tangent to meanline at leading edge, deg, $i = \beta_1 - (\gamma^o + \Delta)$, $i = \alpha - \Delta$
K	Cavitation index, $\frac{p_i - p_v}{p_i - p_i}$
M	Maximum camber of a hydrofoil mean line expressed in percent of chord length
m	Slope factor in deviation angle relation, $m = (\delta^o - \delta_0^o)/\phi$
n	Slope factor in incidence angle relation, $n = (i - i_0)/\phi$
P	Total pressure, lb/sq in.
p	Static pressure, lb/sq in.
p_v	Vapor pressure, lb/sq in.
Δp	Static pressure difference, $p_2 - p_1$, lb/sq in.
q	Dynamic pressure, lb/sq in.
Re_c	Reynolds number based on chord length, $\frac{Vc}{\nu}$
r	Radius, in.
s	Blade spacing, in.

APPENDIX II (Contd.)

t	Maximum profile thickness, in.
V	Velocity, ft/sec
X	Chordal station
y	Coordinate normal to axis, in.
α	Angle-of-attack, angle between inlet-flow direction and blade-chord angle, deg
β	Flow angle, angle between flow direction and axial direction, deg
γ°	Blade chord angle, angle between blade chord and axial direction, deg
Δ	Difference between angle-of-attack and incidence angle, $\Delta = \alpha - i$, deg
δ	Wake full thickness
δ°	Deviation angle, angle between exit-flow direction and tangent to blade mean camber line at trailing edge, $\delta^\circ = \beta_2 - (\gamma^\circ + \Delta - \phi)$ deg
δ^*	Boundary layer displacement thickness, $\int_{\delta/y}^{\delta_{uy}} (1 - \frac{V}{V_0}) dy$
θ	Turning angle, $\beta_1 - \beta_2$, deg
θ^*	Wake momentum-defect thickness, $\int_{\delta/y}^{\delta_{uy}} (1 - \frac{V}{V_0}) \frac{V}{V_0} dy$
ν	Kinematic viscosity, sq ft/sec
ρ	Density, slugs/cu ft
σ	Solidity, ratio of chord to spacing
ϕ	Camber angle, difference between tangent angles at leading and trailing edges, deg
$\bar{w}$	Total pressure loss coefficient

APPENDIX II
(Concluded)

Subscripts

E	Experimental
l_y	Wake boundary from lower surface
N	Nominal
o	Free stream
u_y	Wake boundary from upper surface
1	Station at cascade inlet
2	Station at cascade exit
2D	Two-dimensional
•	Value for zero degree camber hydrofoil

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TABLE I

Coordinates for Multiple Circular-Arc Profiles

	ϕ 0	10	20	25	30	40	45
	M 0	2.10	4.24	5.34	6.45	8.78	10.01
	Δ 0	4.1	8.1	10.1	12.1	16.3	18.5
Chordal Station (inches)	Y (Upper Surface - 1n.)						
0.000	0.0030	0.0030	0.0030	0.0030	0.0030	0.0030	0.0030
0.200	0.0213	0.0290	0.0490	0.0550	0.0625	0.0775	0.0855
0.400	0.0374	0.0650	0.0880	0.1020	0.1145	0.1435	0.1580
0.600	0.0500	0.0870	0.1215	0.1400	0.1600	0.1990	0.2200
0.800	0.0623	0.1070	0.1521	0.1740	0.2000	0.2470	0.2720
1.000	0.0722	0.1230	0.1740	0.2020	0.2300	0.2855	0.3145
1.200	0.0800	0.1370	0.1930	0.2235	0.2535	0.3150	0.3480
1.400	0.0856	0.1460	0.2075	0.2395	0.2710	0.3370	0.3720
1.600	0.0889	0.1510	0.2150	0.2480	0.2815	0.3480	0.3860
1.800	0.0900	0.1530	0.2171	0.2502	0.2835	0.3533	0.3902
2.000	0.0875	0.1485	0.2115	0.2440	0.2775	0.3425	0.3800
2.200	0.0800	0.1365	0.1930	0.2240	0.2565	0.3160	0.3495
2.400	0.0680	0.1170	0.1645	0.1910	0.2170	0.2680	0.2980
2.600	0.0514	0.0875	0.1240	0.1438	0.1610	0.2020	0.2240
2.800	0.0300	0.0500	0.0710	0.0820	0.0900	0.1145	0.1265
3.000	0.0030	0.0030	0.0030	0.0030	0.0030	0.0030	0.0030
	Y (Lower Surface - 1n.)						
0.000	-0.0030	-0.0030	-0.0030	-0.0030	-0.0030	-0.0030	-0.0030
0.200	-0.0213	-0.0065	0.0050	0.0120	0.0190	0.0350	0.0415
0.400	-0.0374	-0.0120	0.0120	0.0255	0.0385	0.0680	0.0810
0.600	-0.0500	-0.0160	0.0200	0.0385	0.0565	0.0965	0.1160
0.800	-0.0623	-0.0190	0.0260	0.0480	0.0725	0.1205	0.1450
1.000	-0.0722	-0.0220	0.0290	0.0565	0.0845	0.1400	0.1685
1.200	-0.0800	-0.0240	0.0325	0.0625	0.0930	0.1545	0.1870
1.400	-0.0856	-0.0260	0.0360	0.0678	0.0990	0.1650	0.2000
1.600	-0.0889	-0.0265	0.0366	0.0697	0.1020	0.1710	0.2080
1.800	-0.0900	-0.0270	0.0371	0.0702	0.1035	0.1733	0.2102
2.000	-0.0875	-0.0260	0.0355	0.0685	0.1010	0.1690	0.2045
2.200	-0.0800	-0.0240	0.0330	0.0628	0.0960	0.1540	0.1860
2.400	-0.0680	-0.0210	0.0265	0.0520	0.0790	0.1295	0.1575
2.600	-0.0514	-0.0175	0.0190	0.0375	0.0555	0.0945	0.1160
2.800	-0.0300	-0.0110	0.0090	0.0190	0.0280	0.0500	0.0600
3.000	-0.0300	-0.0300	-0.0300	-0.0300	-0.0300	-0.0300	-0.0300

Table II

Index to Cascade Test Configurations

<u>Inlet Flow Angle (Deg)</u>	<u>Camber Angle (Deg)</u>	<u>Solidity</u>	<u>Fig. No.</u>
60	0	0.75	11
	0	1.00	12
	0	1.50	13
	20	0.75	14
	20	1.00	15
	20	1.50	16
	30	0.75	17
	30	1.00	18
	30	1.50	19
	40	0.75	20
	40	1.00	21
	40	1.50	22
	45	0.75	23
	45	1.00	24
	45	1.50	25
70	0	0.75	26
	0	1.00	27
	0	1.50	28
	20	0.75	29
	20	1.00	30
	20	1.50	31
	25	0.75	32
	25	1.00	33
	25	1.50	34
	30	0.75	35
	30	1.00	36
	30	1.50	37
75	0	0.75	38
	0	1.00	39
	0	1.50	40
	10	0.75	41
	10	1.00	42
	10	1.50	43
	20	0.75	44
	20	1.00	45
	20	1.50	46
	25	0.75	47
	25	1.00	48
	25	1.50	49

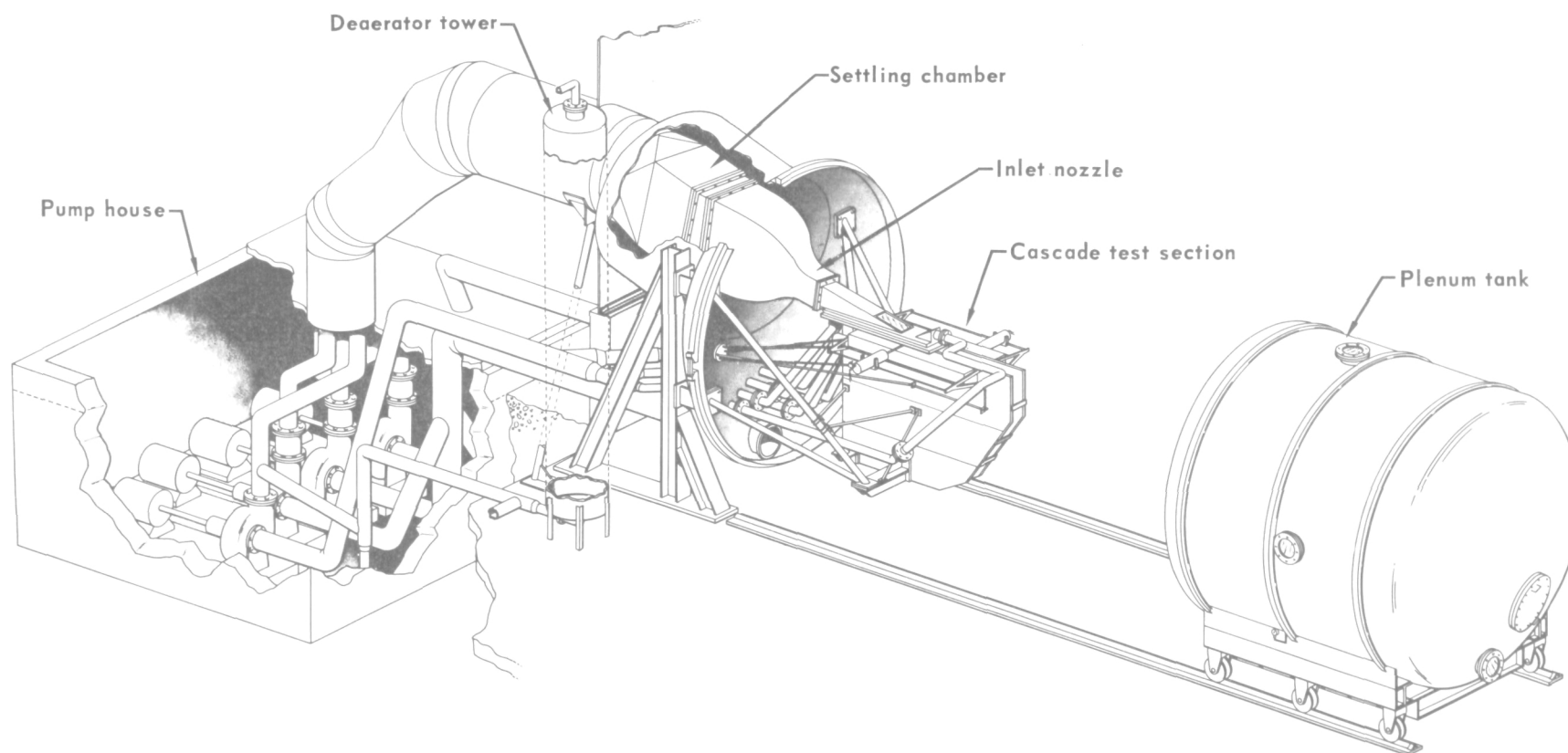


Figure 1. - Cascade water tunnel.

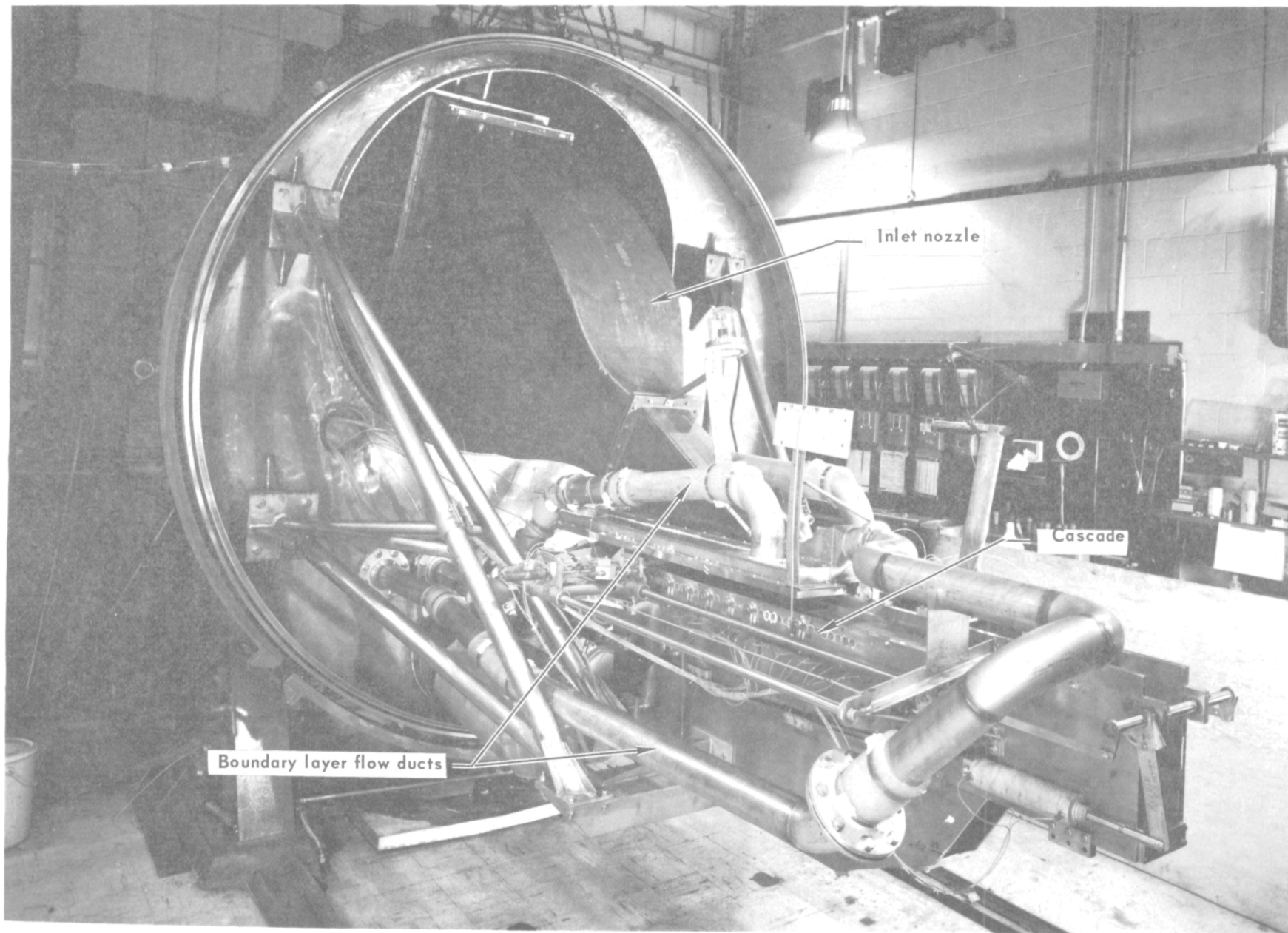


Figure 2. — Sixty degree inlet installation.

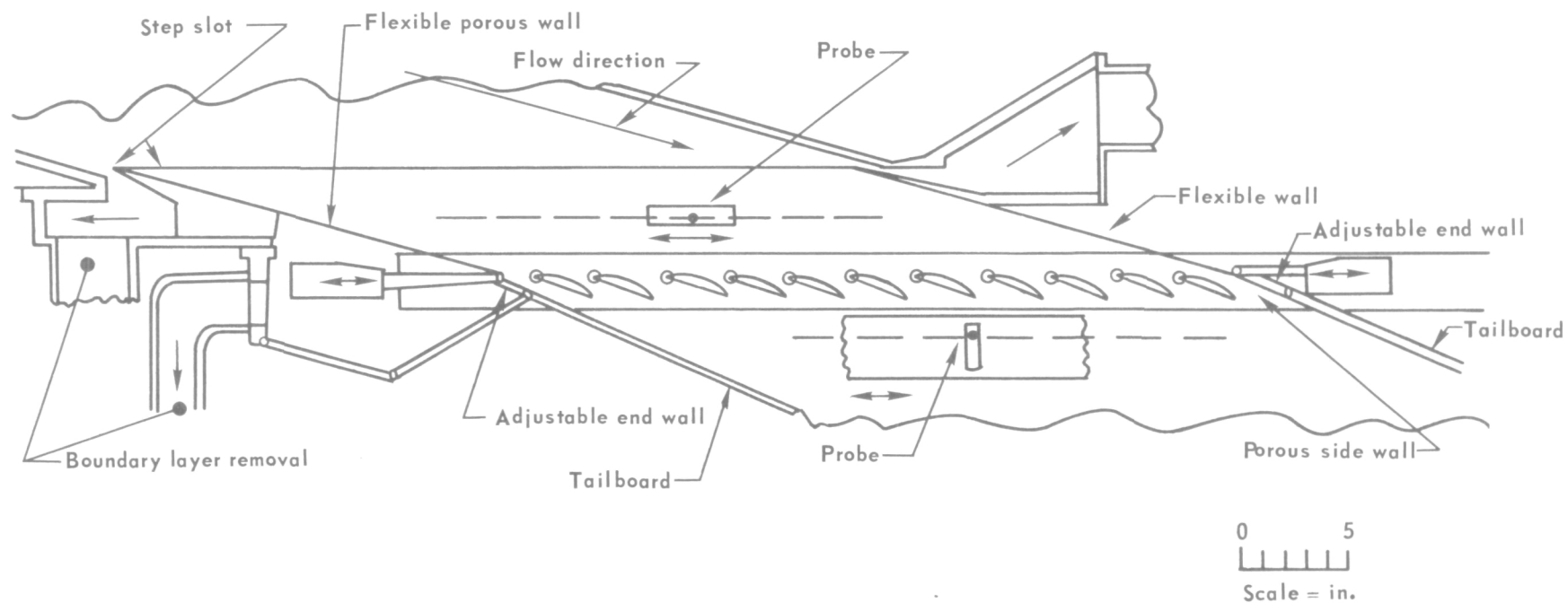


Figure 3. - Cascade test section.

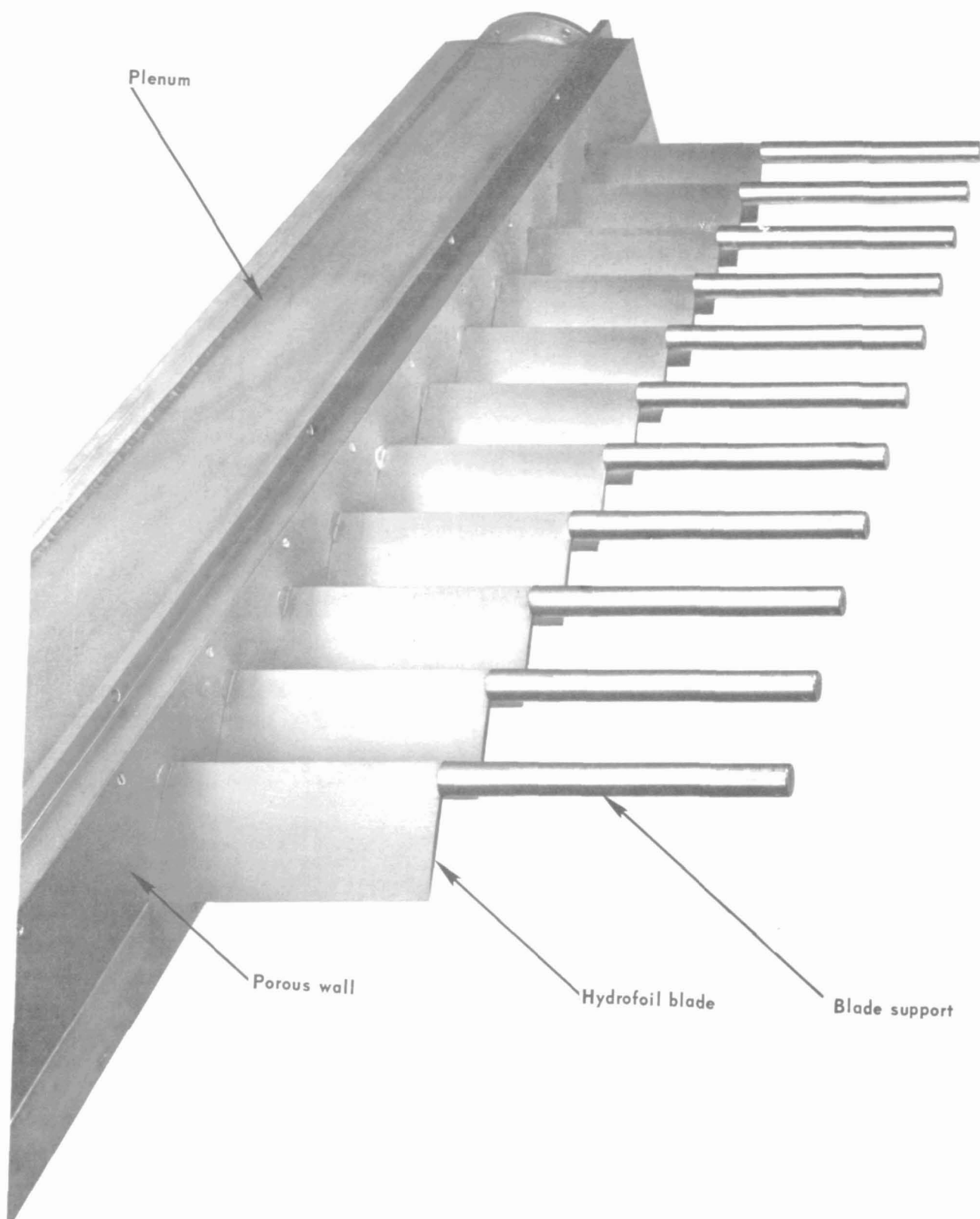
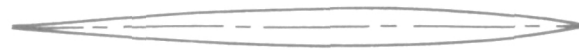


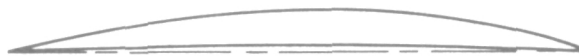
Figure 4. - Porous sidewall assembly.



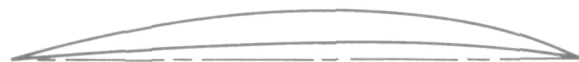
$\phi = 0$ $M = 0$



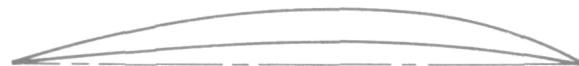
$\phi = 10$ $M = 2.10$



$\phi = 20$ $M = 4.24$



$\phi = 25$ $M = 5.34$



$\phi = 30$ $M = 6.45$

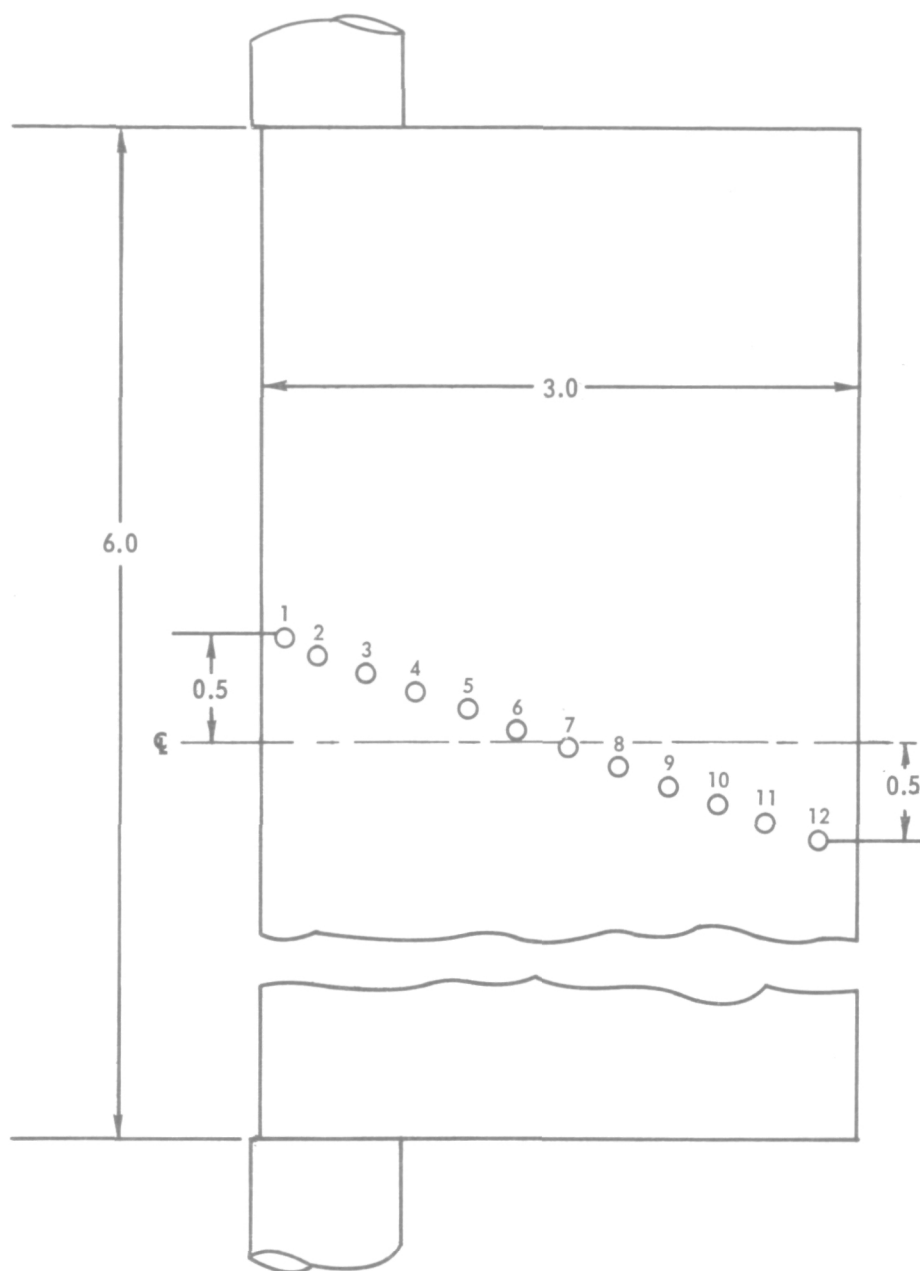


$\phi = 40$ $M = 8.78$

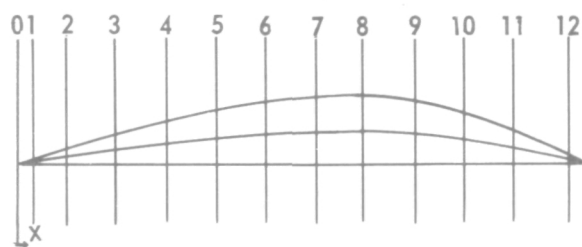


$\phi = 45$ $M = 10.01$

Figure 5. — Multiple circular-arc (NACA M606) profiles.



NO.	X	% CHORD
1	0.125	4.16
2	0.250	8.33
3	0.500	16.67
4	0.750	25.00
5	1.000	33.33
6	1.250	41.60
7	1.500	50.00
8	1.750	58.33
9	2.000	66.67
10	2.250	75.00
11	2.500	83.33
12	2.750	91.67



Note: All dimensions are in inches

Figure 6. - Location of static pressure instrumentation - suction and pressure surfaces.

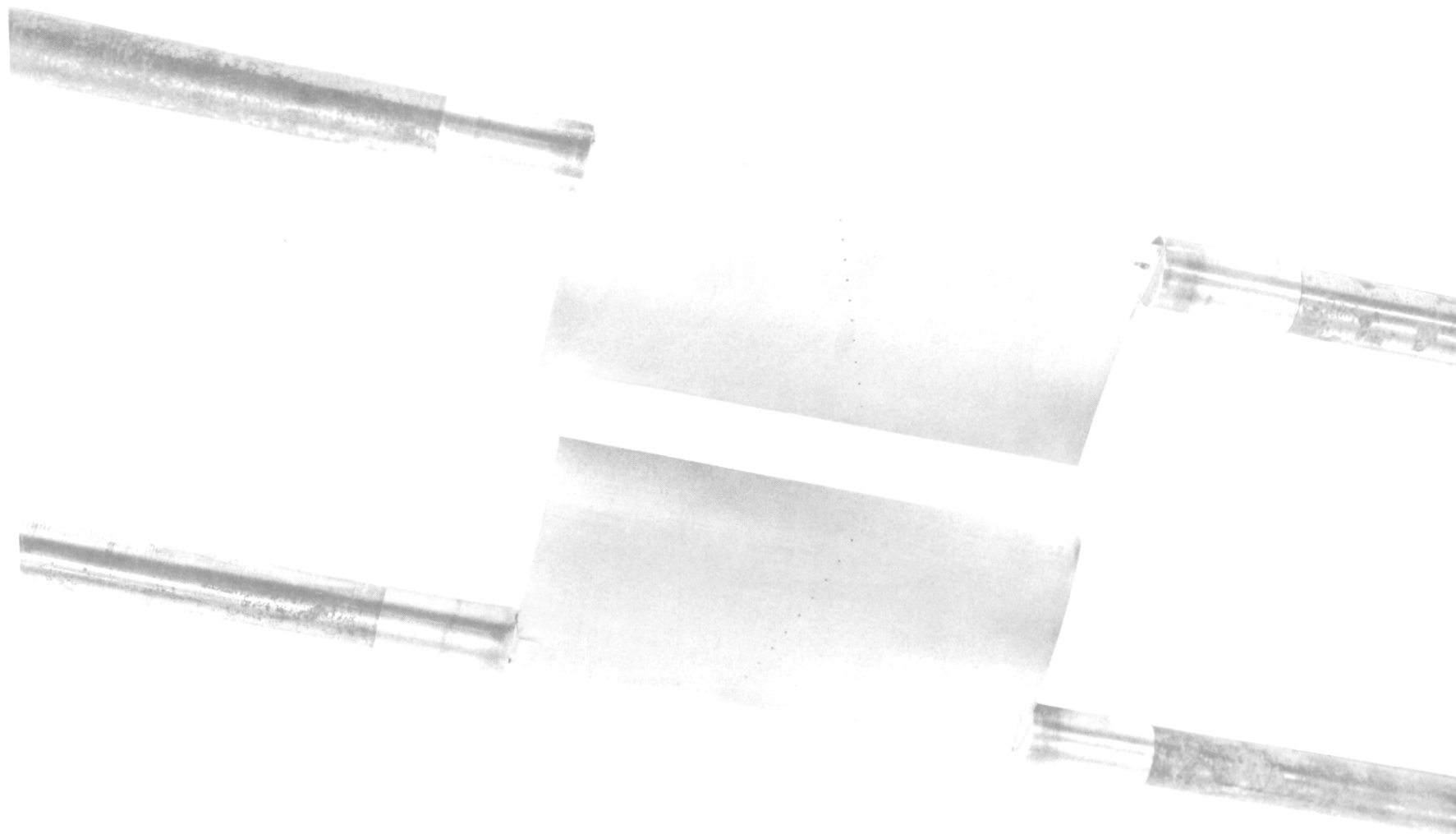


Figure 7. — Static pressure instrumentation in 40-degree camber multiple circular-arc (NACA M606) hydrofoils.



a. Wedge (upstream)



b. Kiel-wedge combination
(downstream)

Figure 8. -Directional probes .

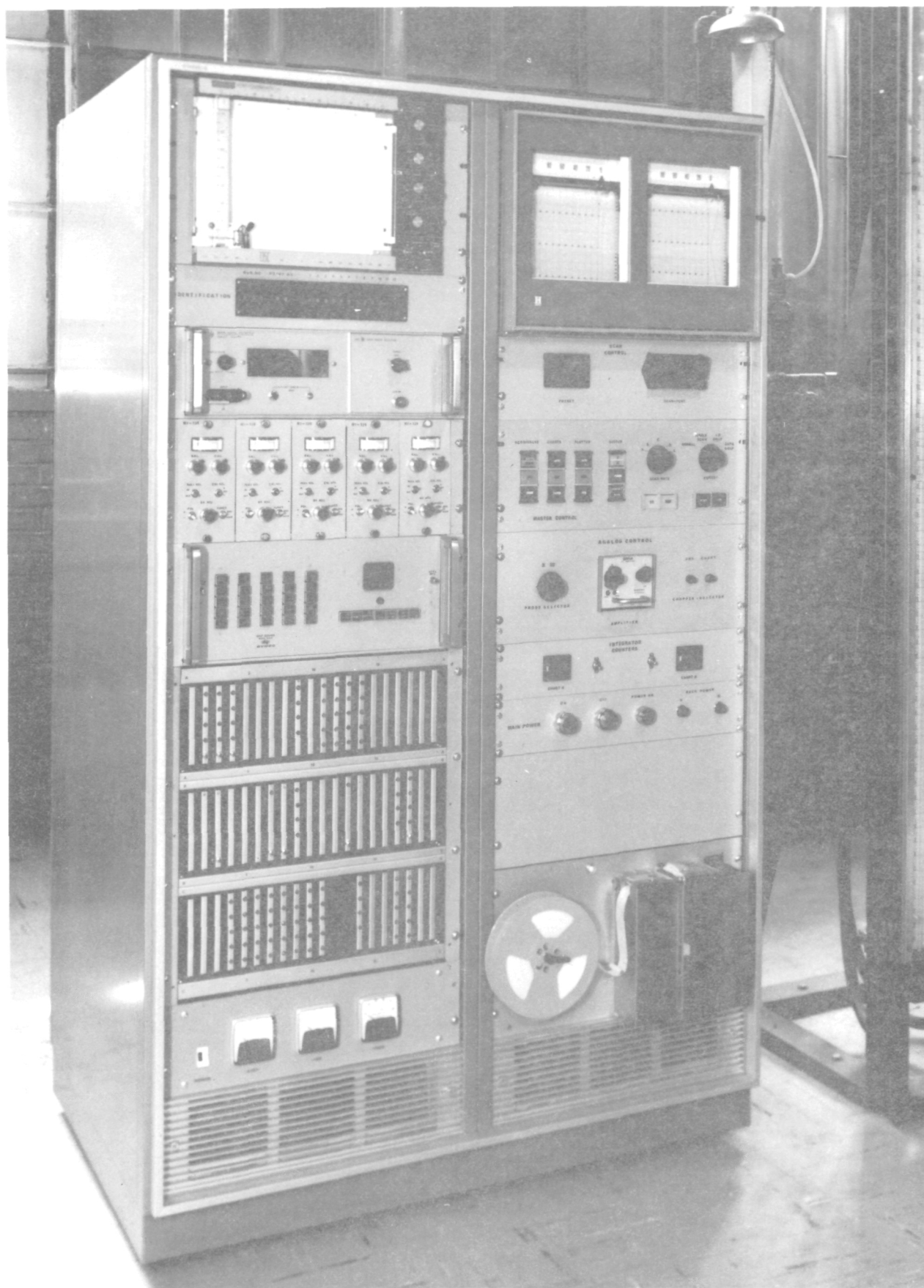
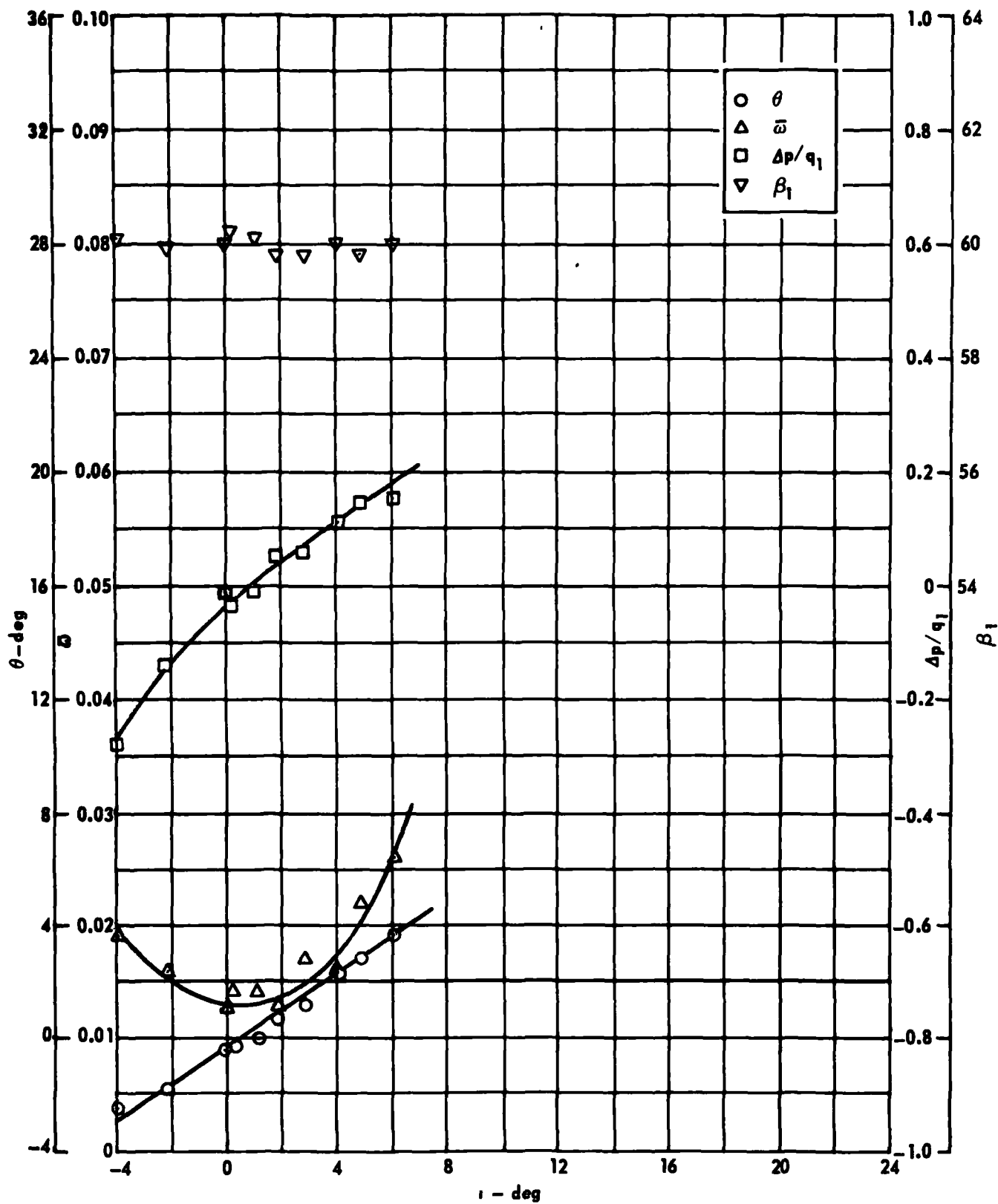


Figure 9. - Data acquisition system.

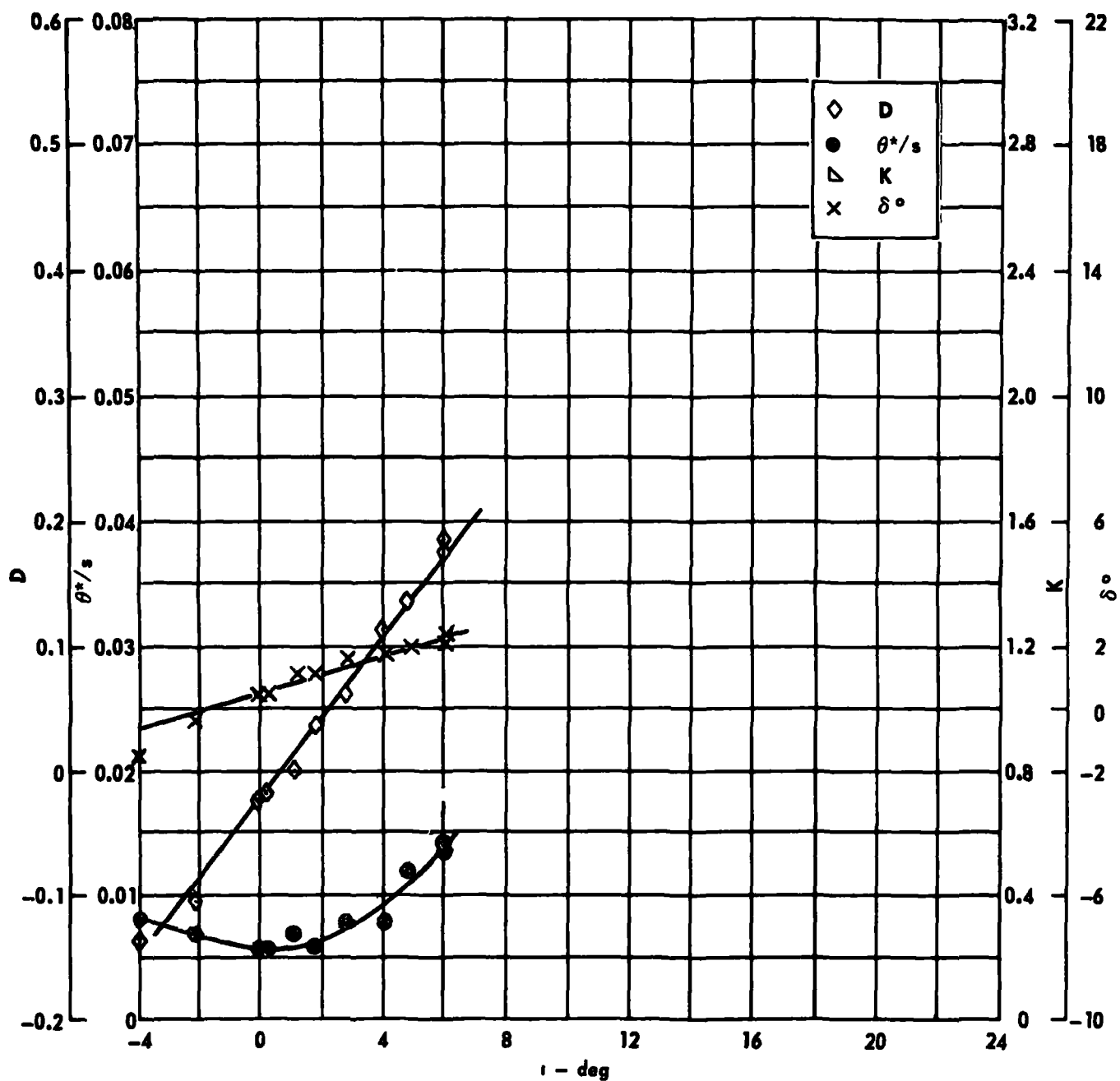


Cascade configuration $\beta_{1N} = 60, \sigma = 0.75$

M606 profile $\phi = 0, t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 11. - Cascade characteristics as functions of incidence.



Cascade configuration $\beta_{1N} = 60$, $\sigma = 0.75$

M606 profile $\phi = 0$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 11. - Concluded.

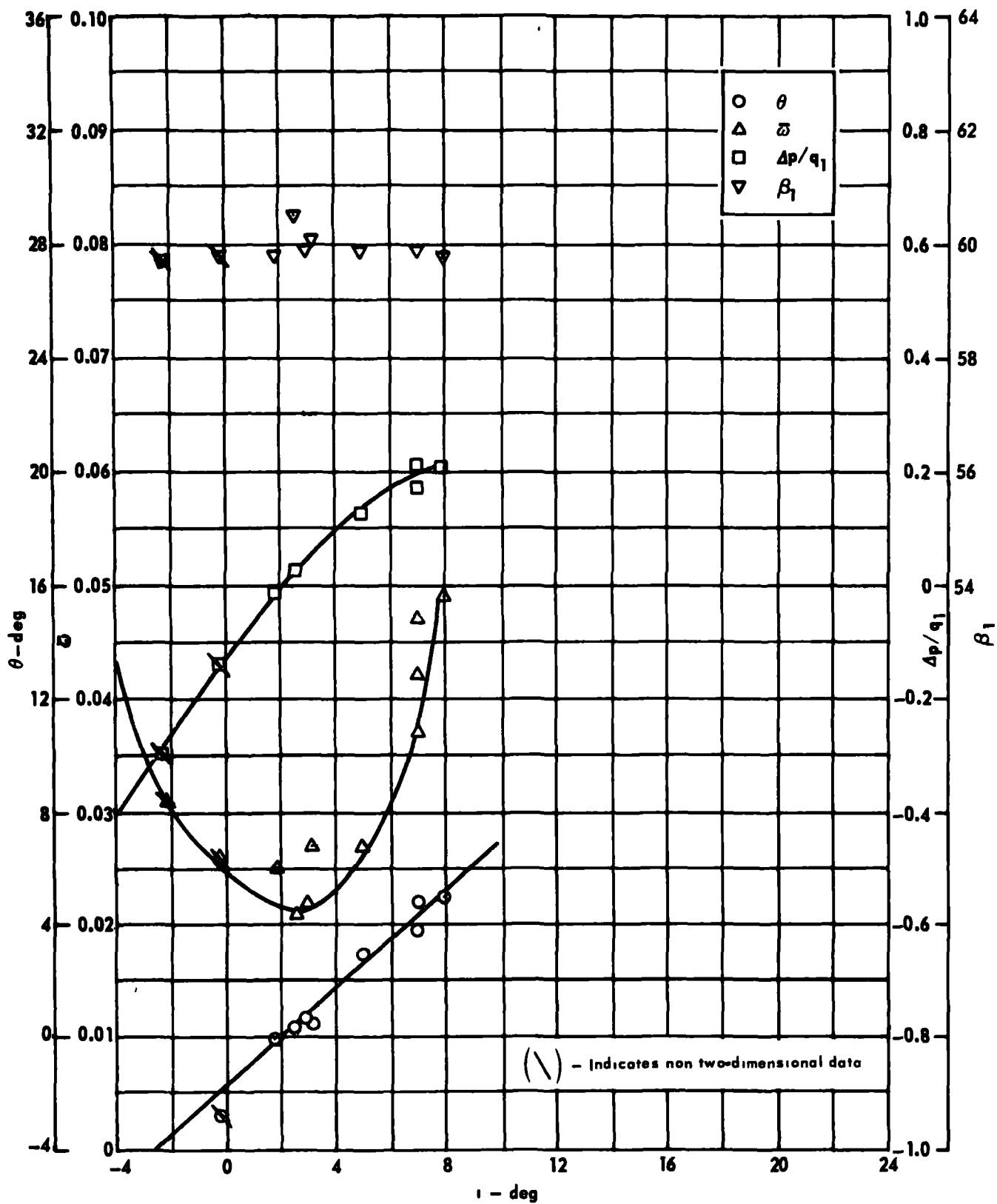
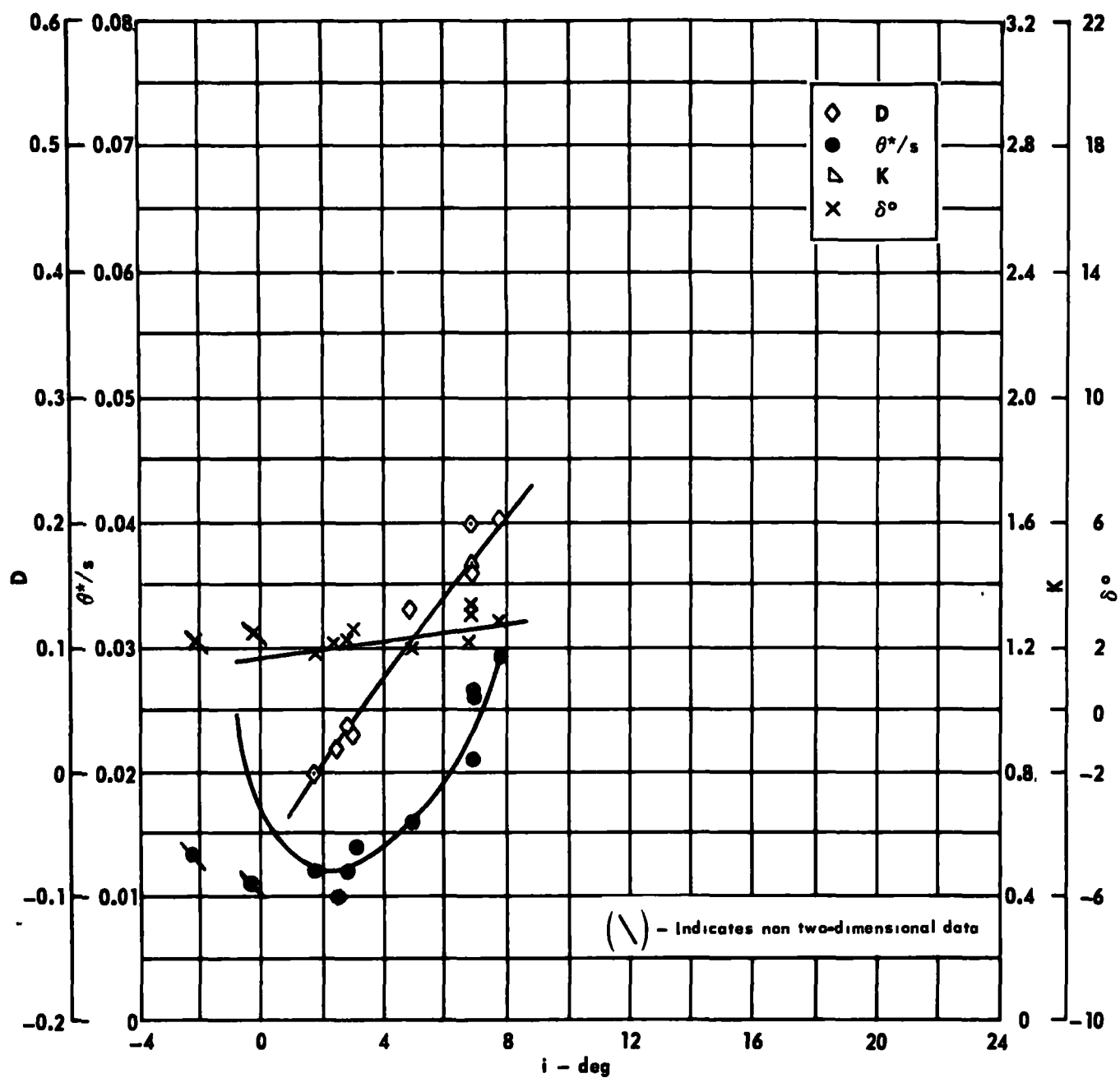


Figure 12. - Cascade characteristics as functions of incidence.

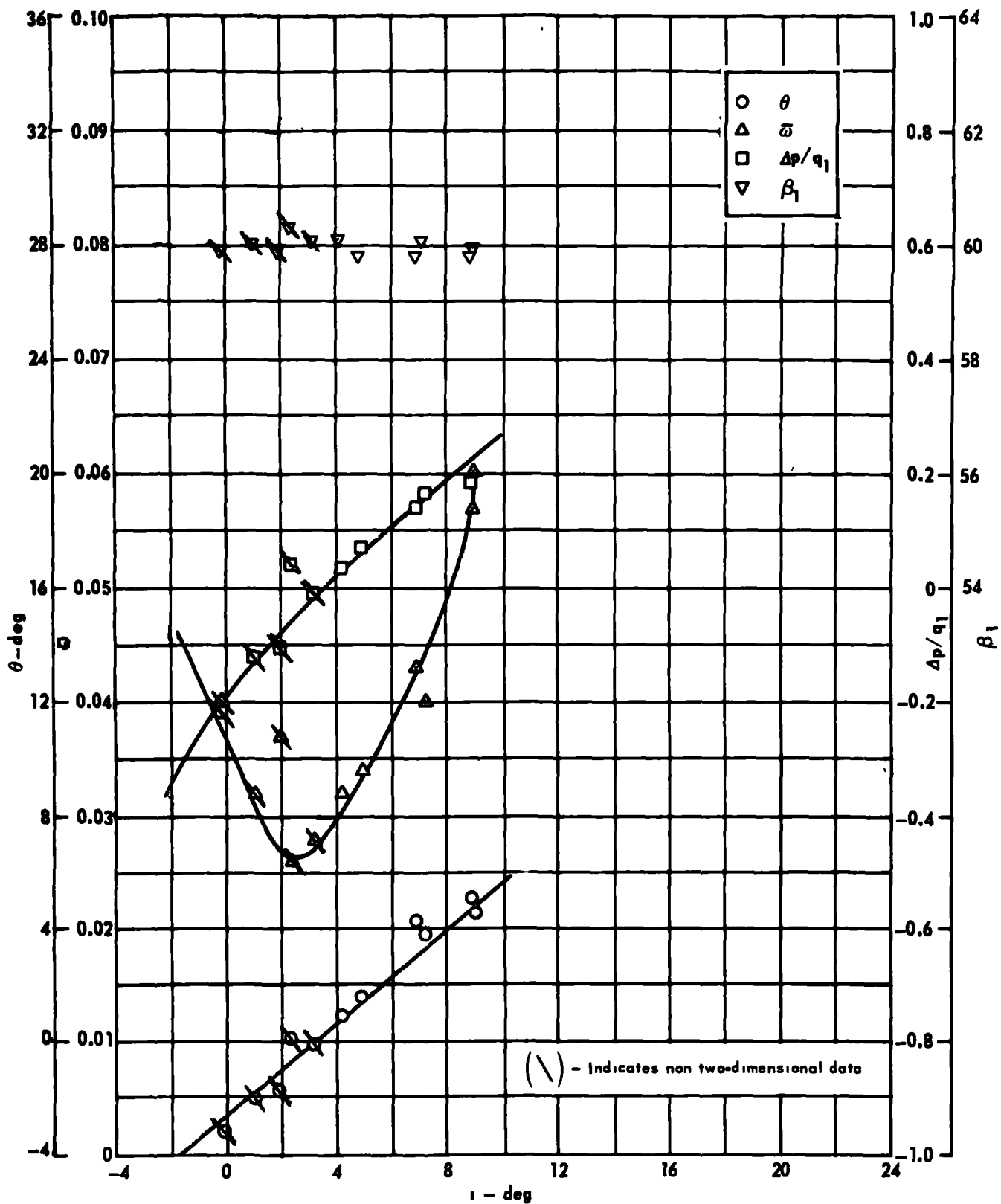


Cascade configuration $\beta_N = 60$, $\sigma = 1.00$

M606 profile $\phi = 0$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 12. - Concluded.

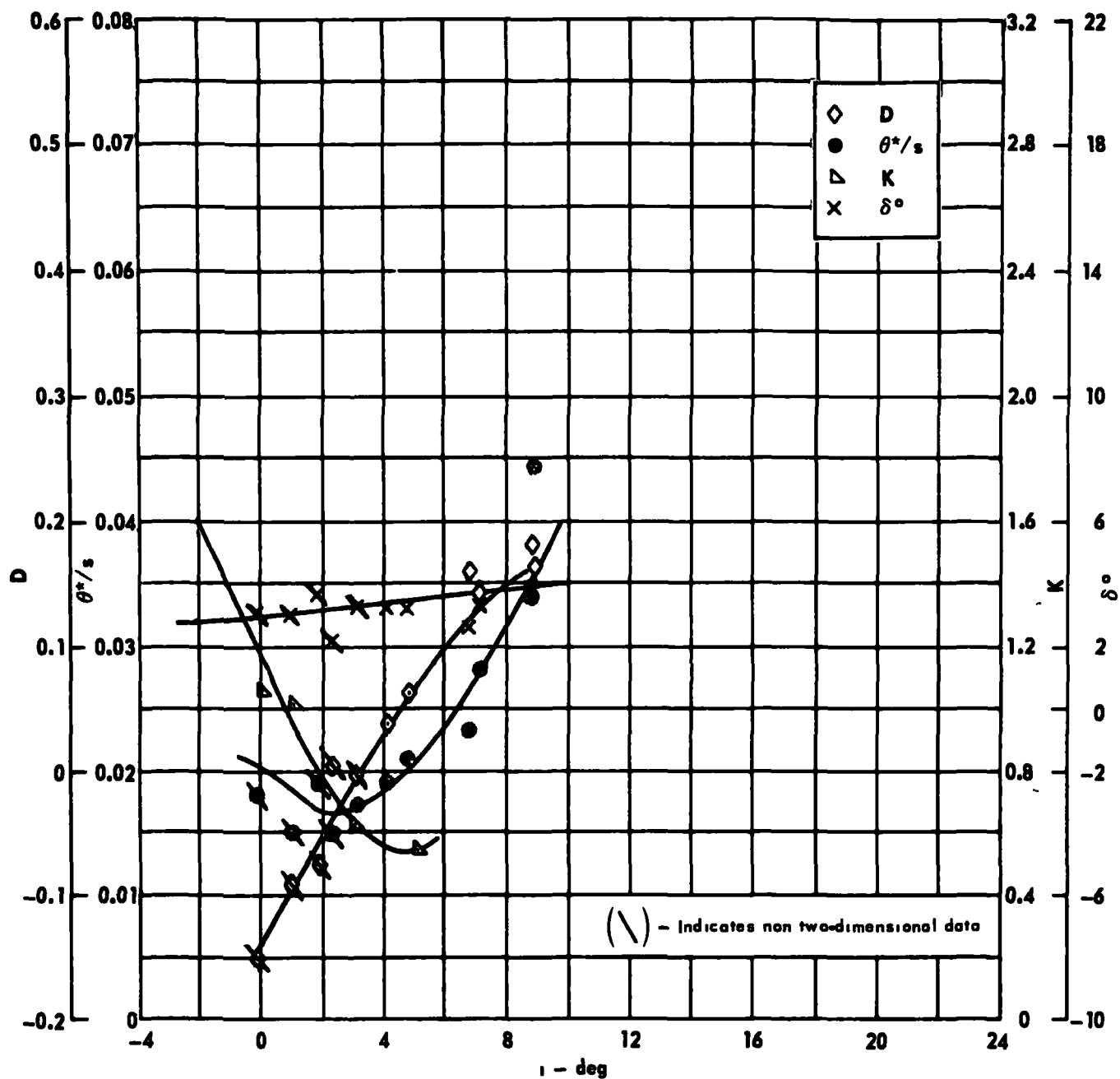


Cascade configuration $\beta_{1N} = 60$, $\sigma = 1.50$

M606 profile $\phi = 0$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 13. - Cascade characteristics as functions of incidence.

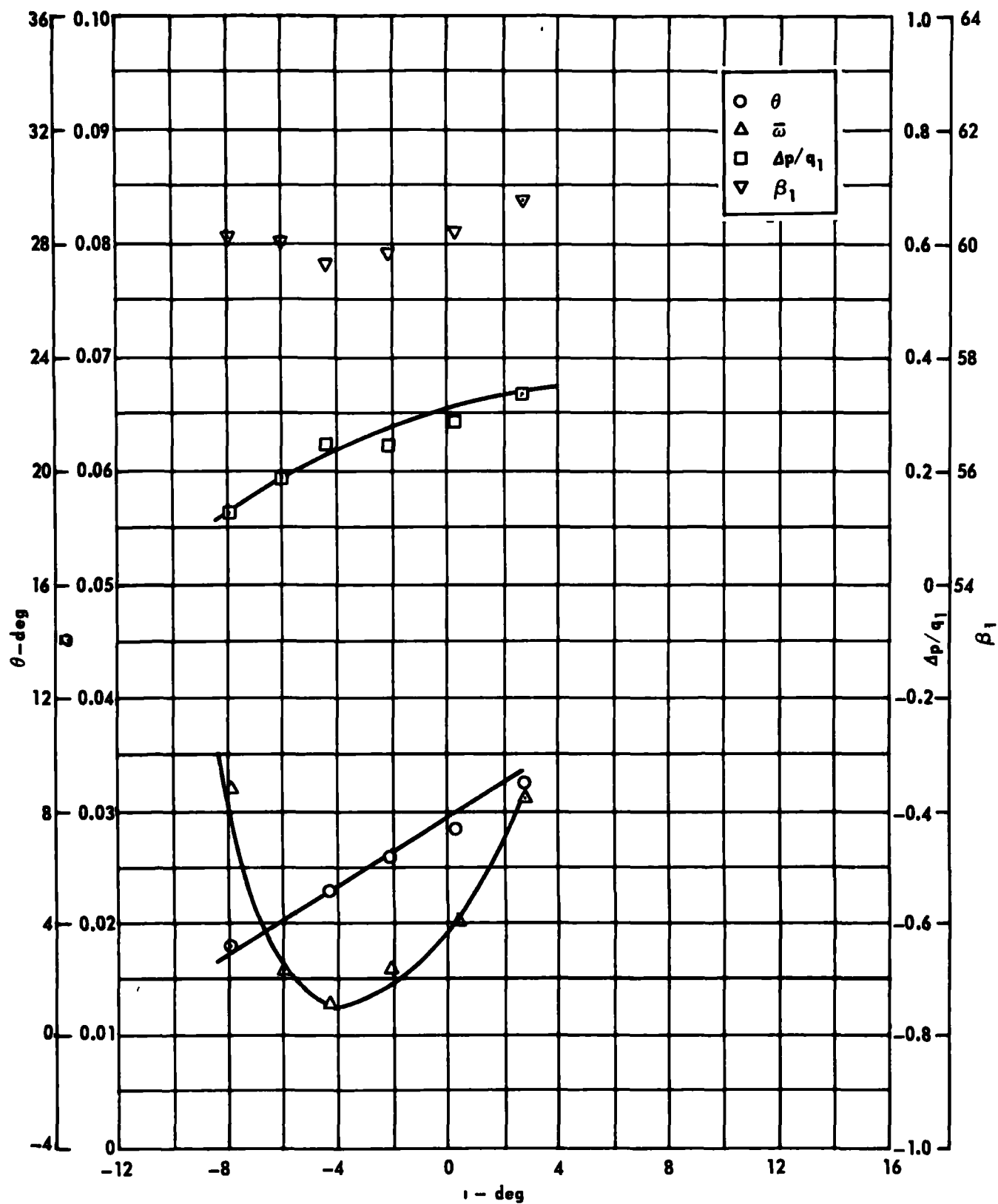


Cascade configuration $\beta_{1N} = 60, \sigma = 1.50$

M606 profile: $\phi = 0, t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 13. - Concluded.

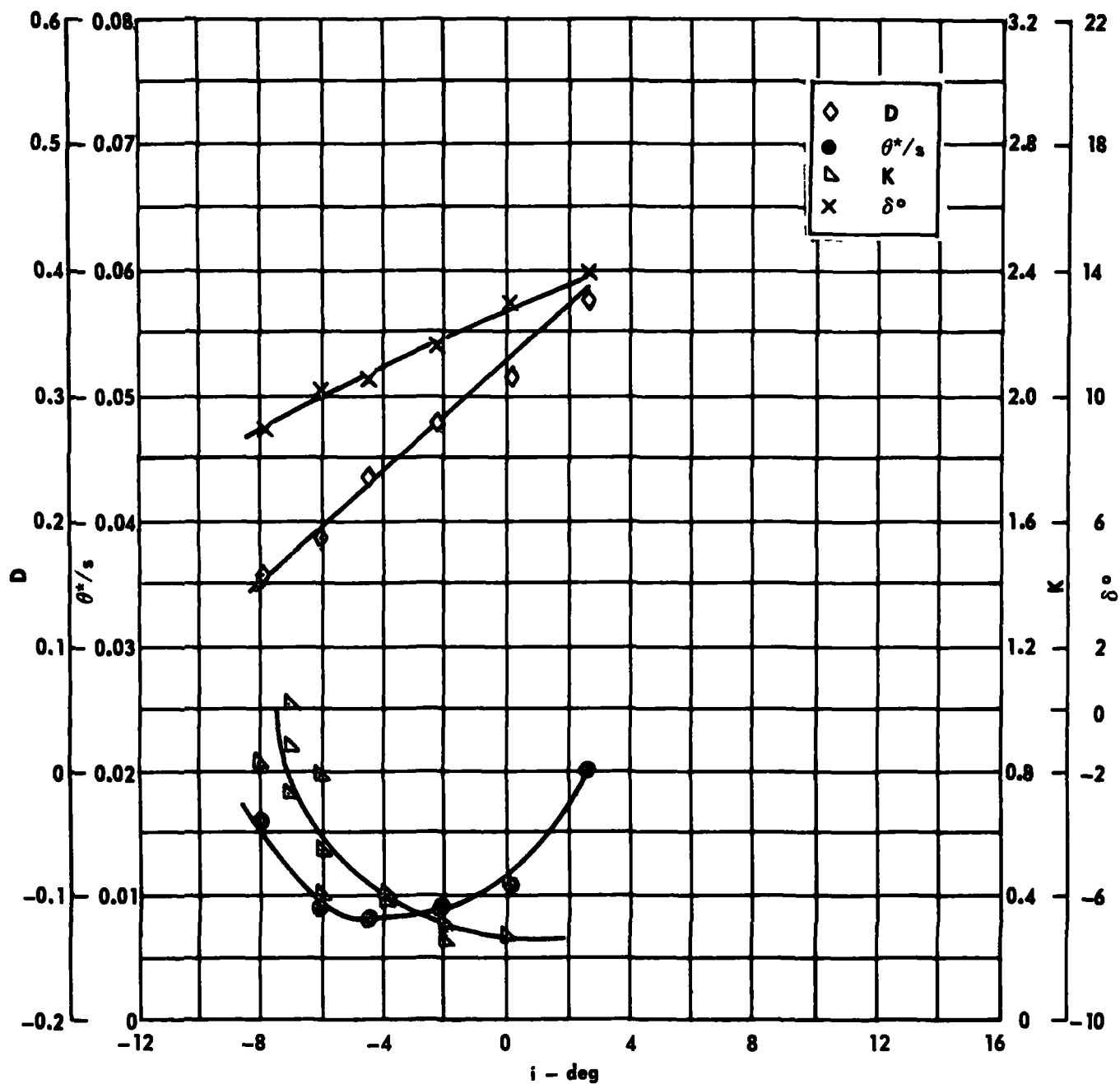


Cascade configuration $\beta_{1N} = 60, \sigma = 0.75$

M606 profile $\phi = 20, t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 14. - Cascade characteristics as functions of incidence.

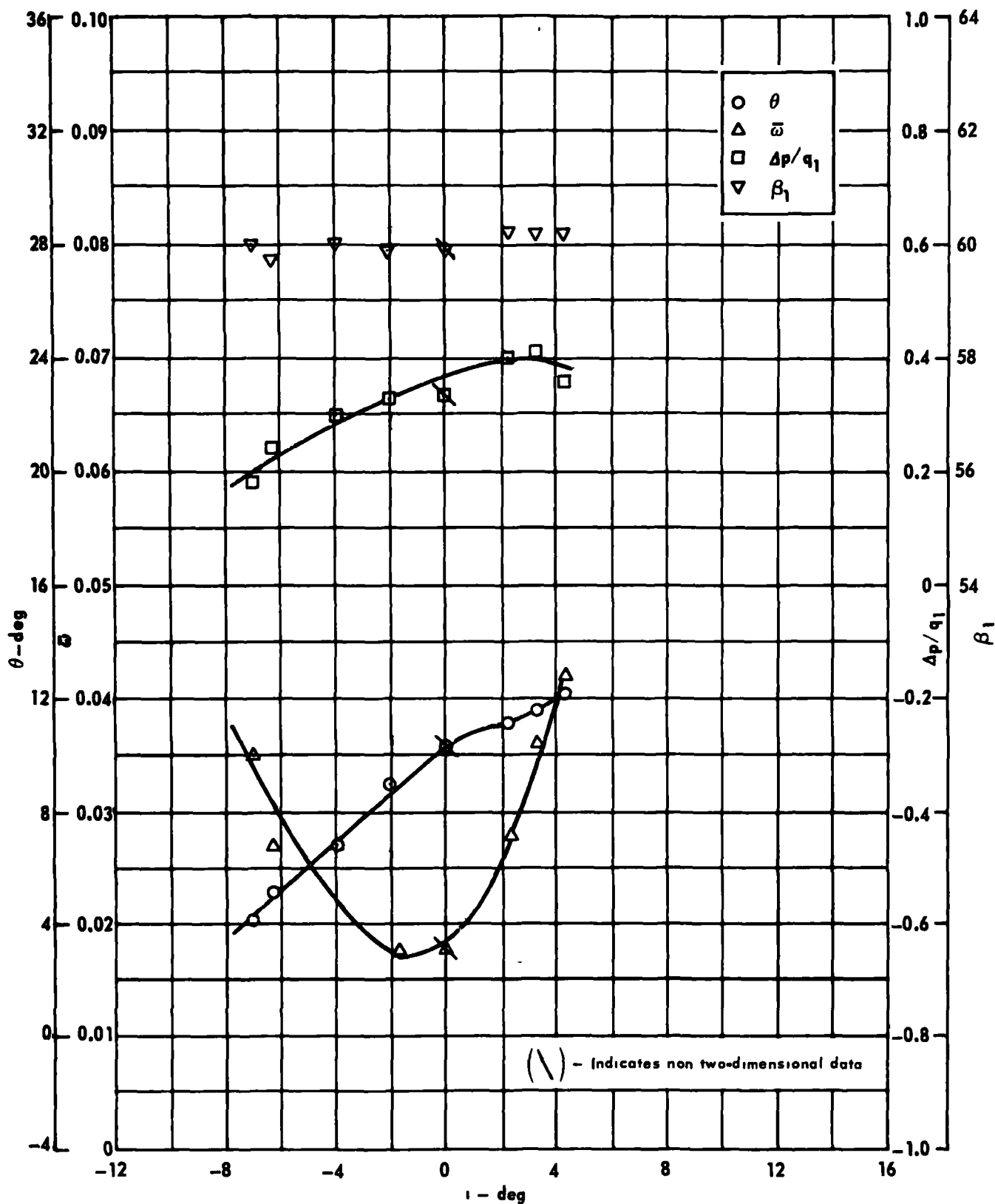


Cascade configuration $\beta_{1N} = 60, \sigma = 0.75$

M606 profile : $\phi = 20, t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 14. - Concluded.

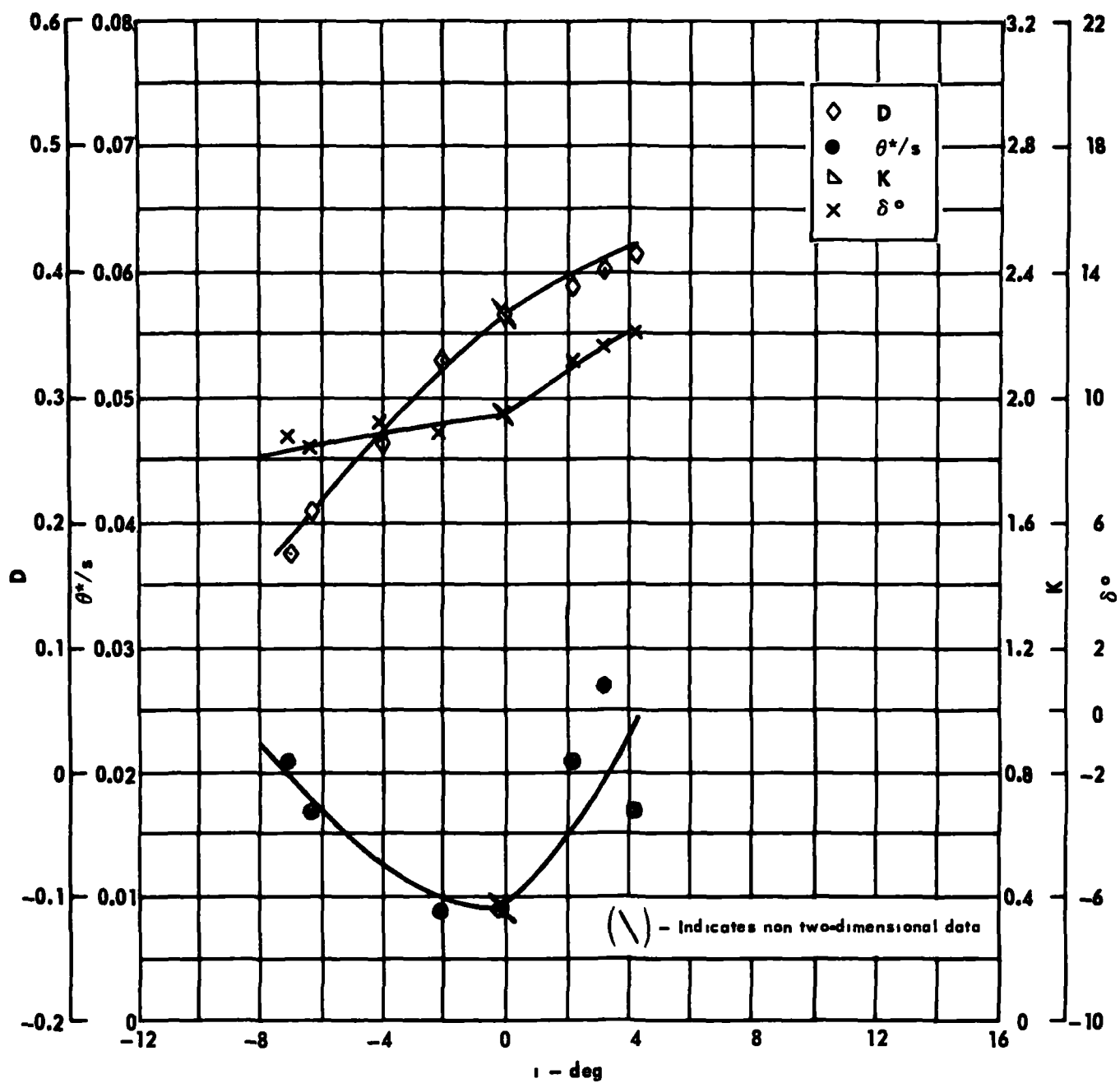


Cascade configuration $\beta_{1N} = 60$, $\sigma = .00$,

M606 profile $\phi = 20$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 15. - Cascade characteristics as functions of incidence.

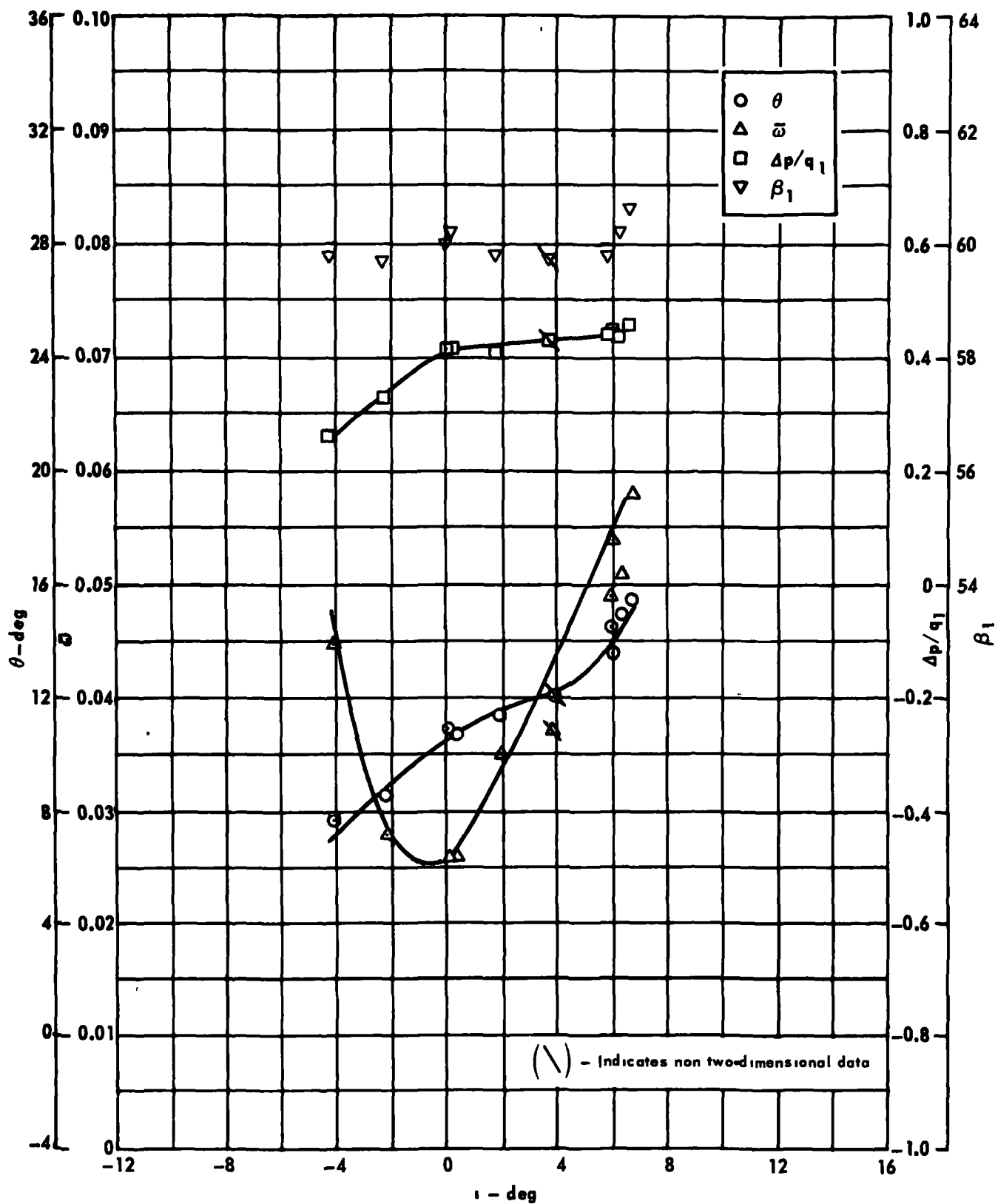


Cascade configuration $\beta_{1N} = 60, \sigma = 1.00$

M606 profile $\phi = 20, t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 15. - Concluded.

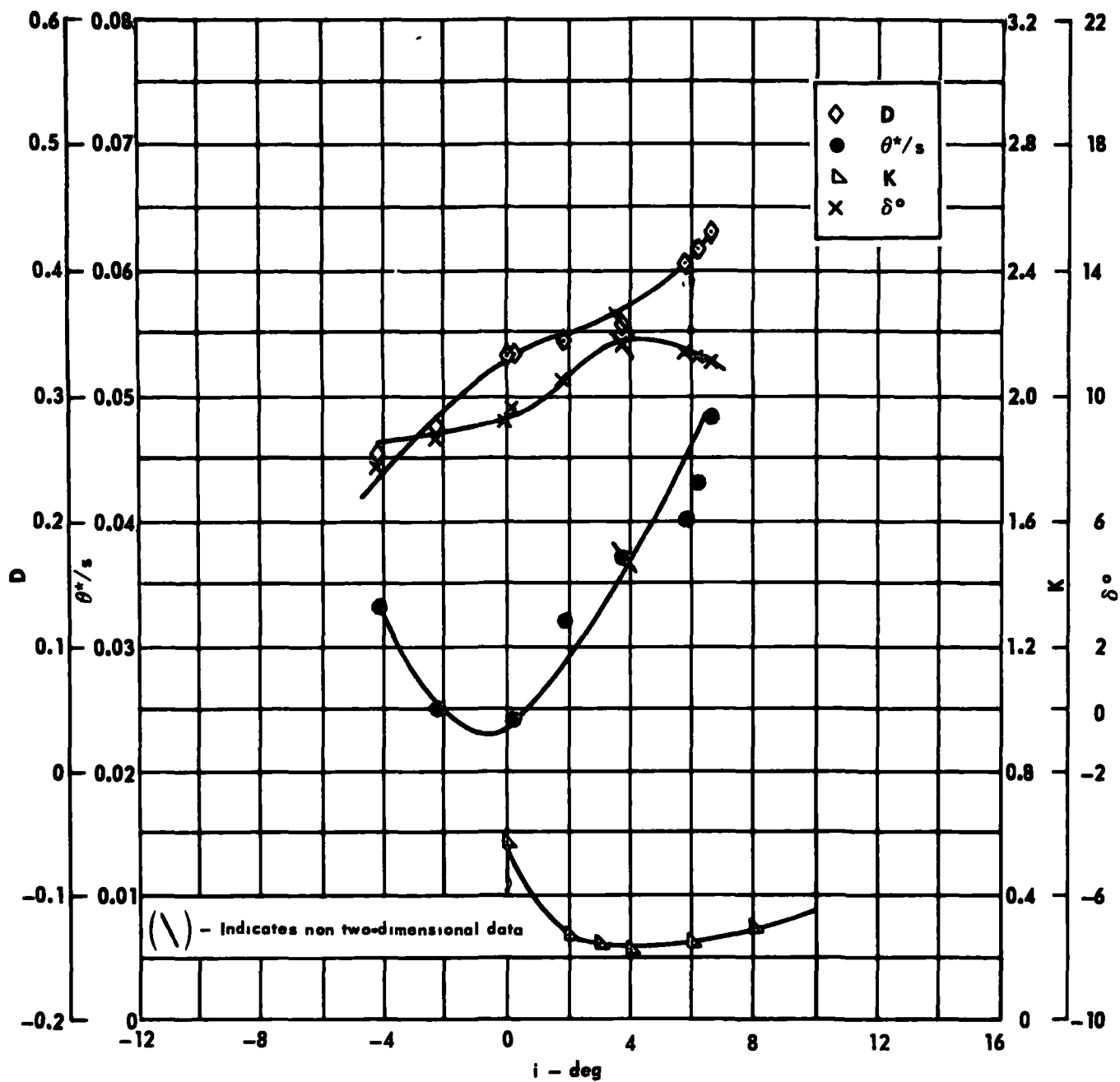


Cascade configuration $\beta_{1N} = 60$, $\sigma = 1.50$

M606 profile $\phi = 20$, $t/c = 0.06$

(a) $\theta, \bar{w}, \Delta p/q_1, \beta_1$

Figure 16. - Cascade characteristics as functions of incidence.

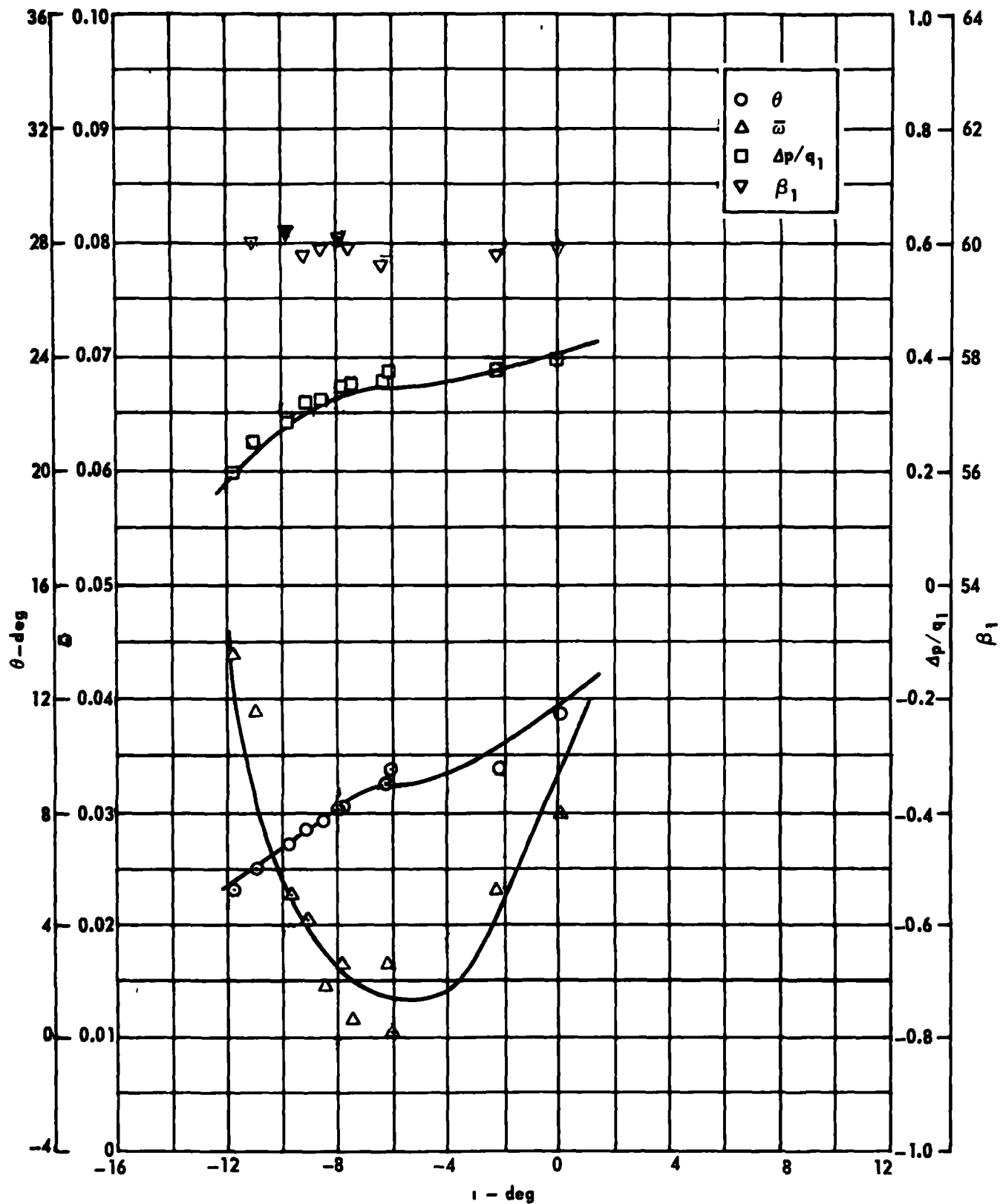


Cascade configuration $\beta_{1N} = 60, \sigma = 1.50$

M606 profile : $\phi = 20, t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 16. - Concluded.

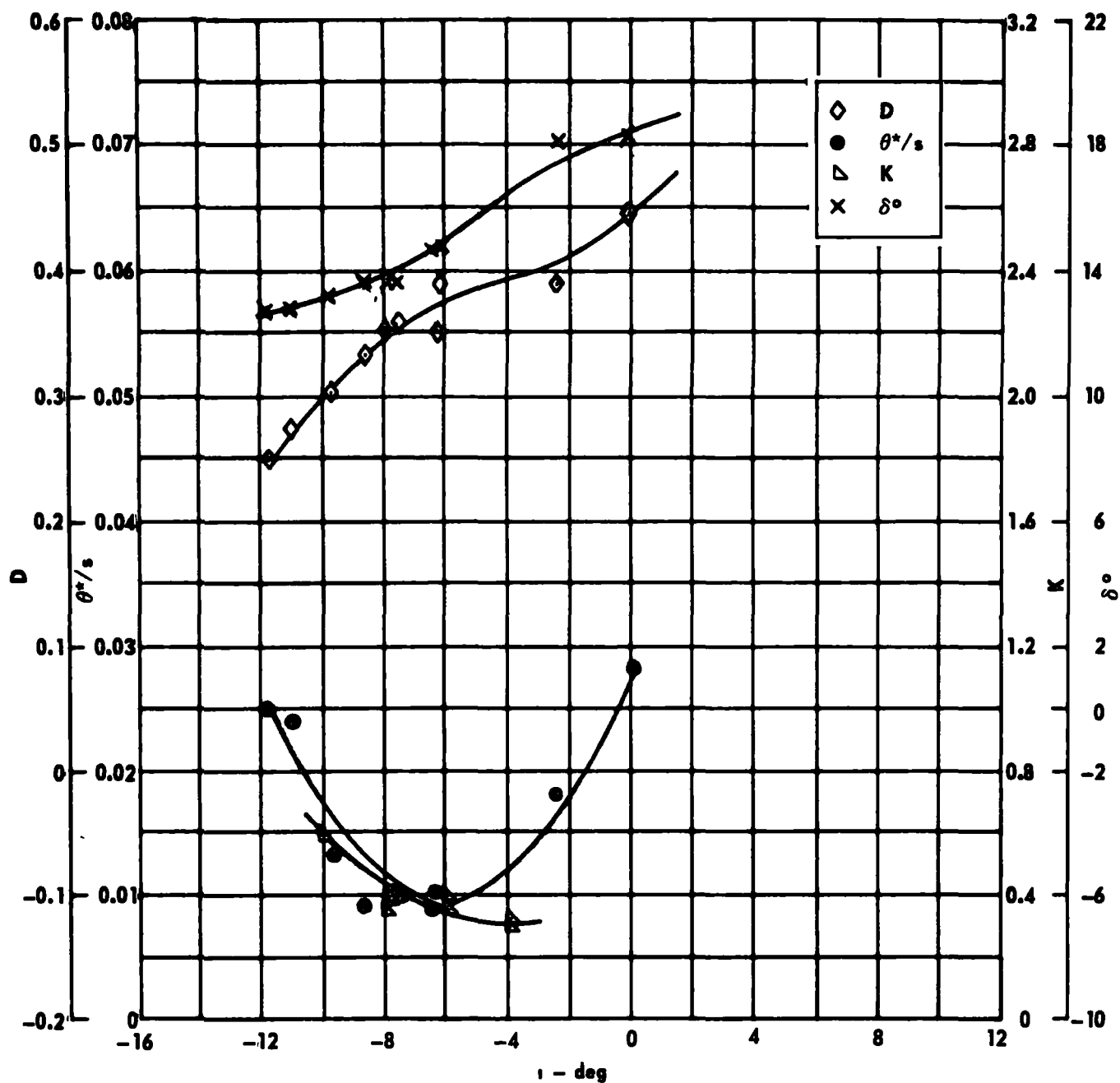


Cascade configuration $\beta_{1N} = 60, \sigma = 0.75$

M606 profile $\phi = 30, t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p / q_1, \beta_1$

Figure 17. - Cascade characteristics as functions of incidence.

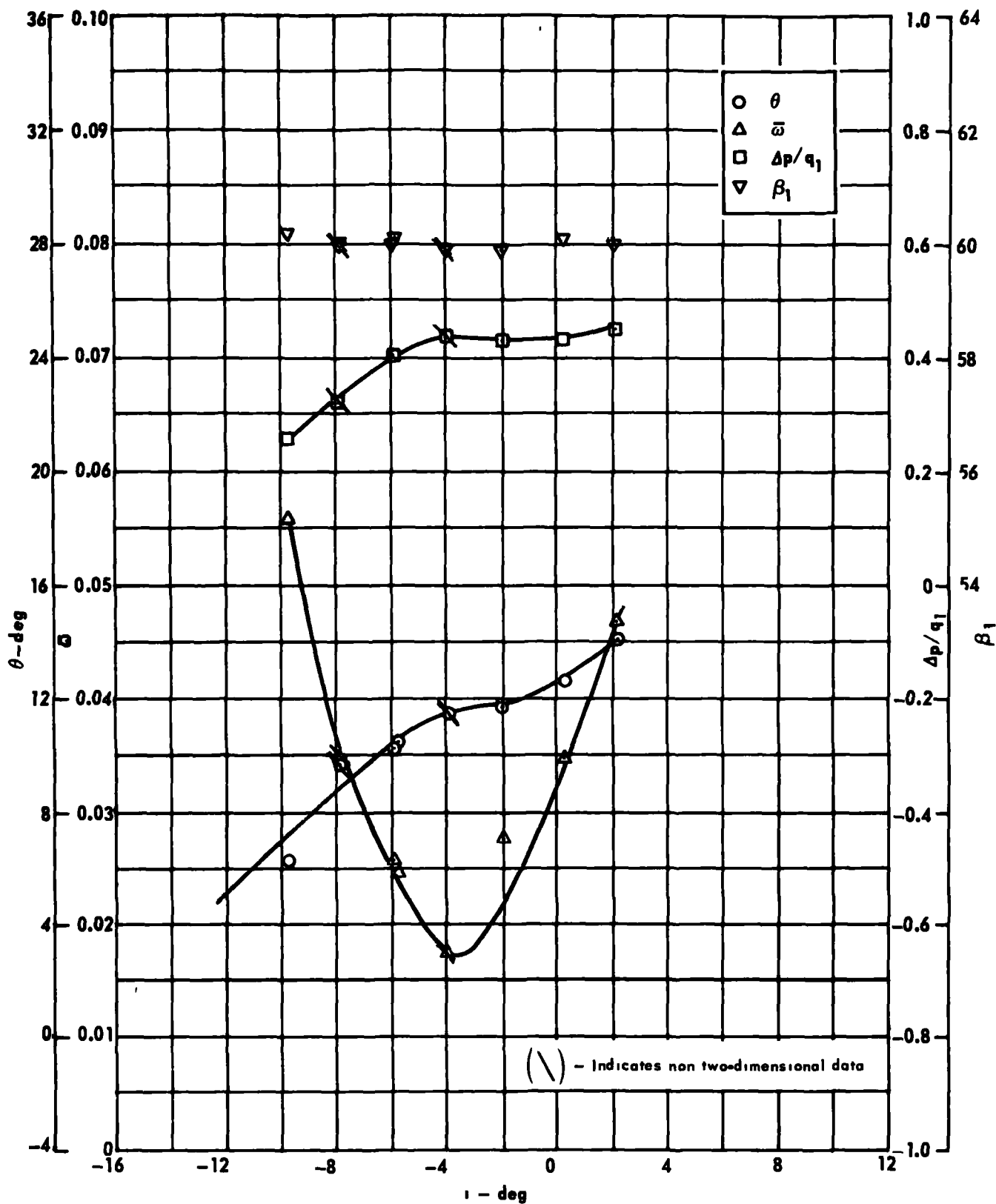


Cascade configuration $\beta_{1N} = 60, \sigma = 0.75$

M606 profile $\phi = 30, t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 17. - Concluded.

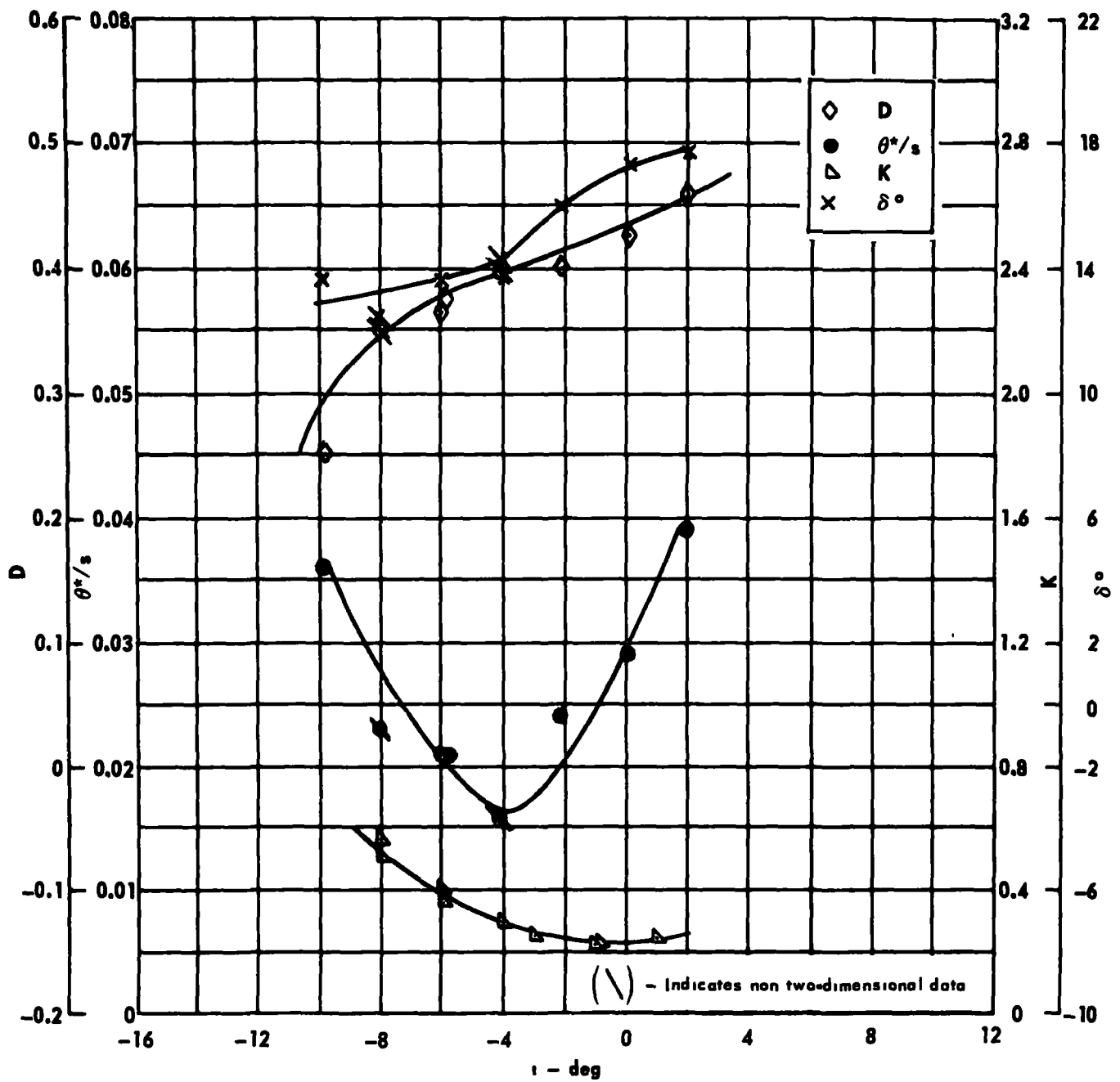


Cascade configuration $\beta_{1N} = 60, \sigma = 1.00$

M606 profile $\phi = 30, t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 18. - Cascade characteristics as functions of incidence.



Cascade configuration $\beta_N = 60$, $\sigma = 1.00$

M606 profile $\phi = 30$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 18. - Concluded.

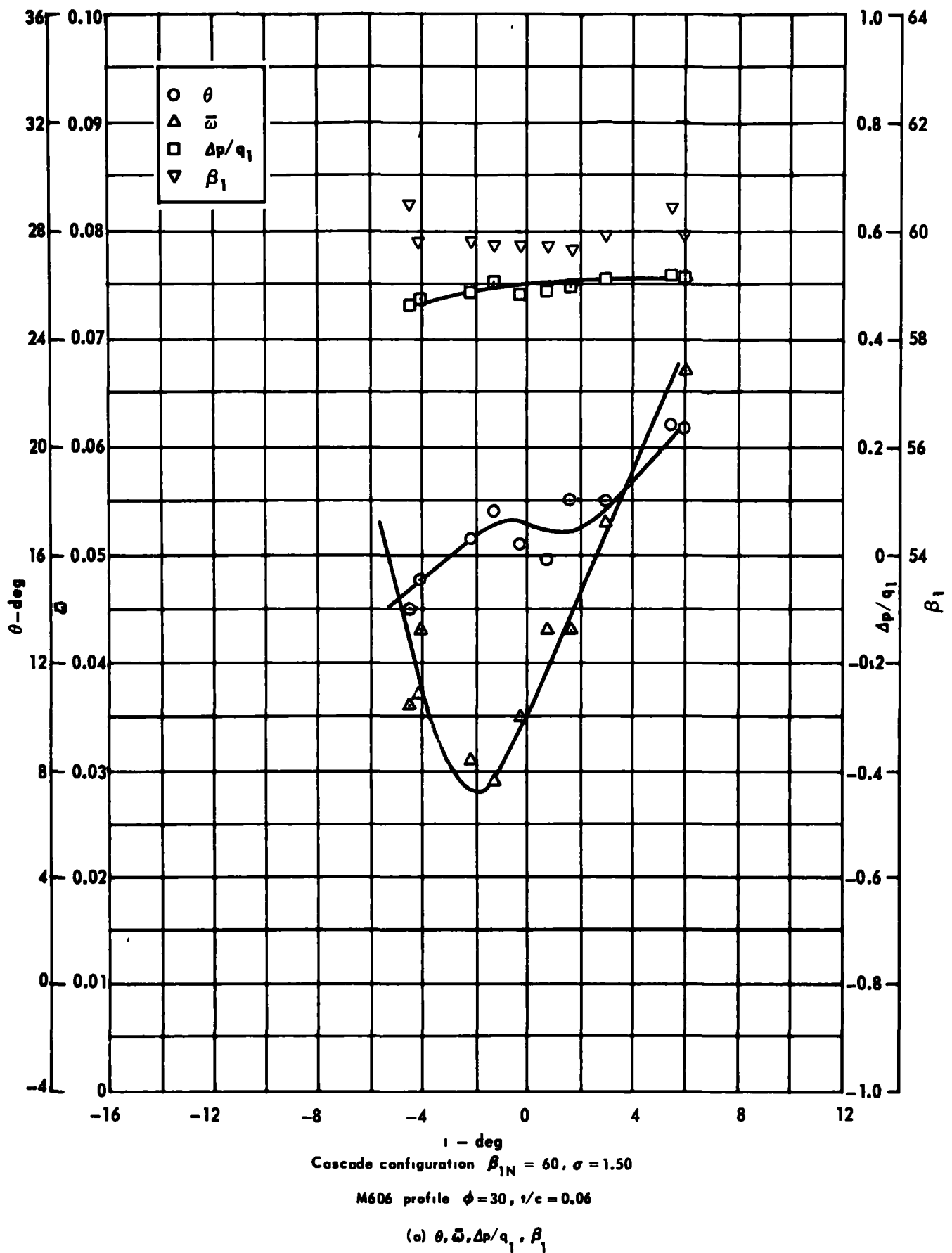
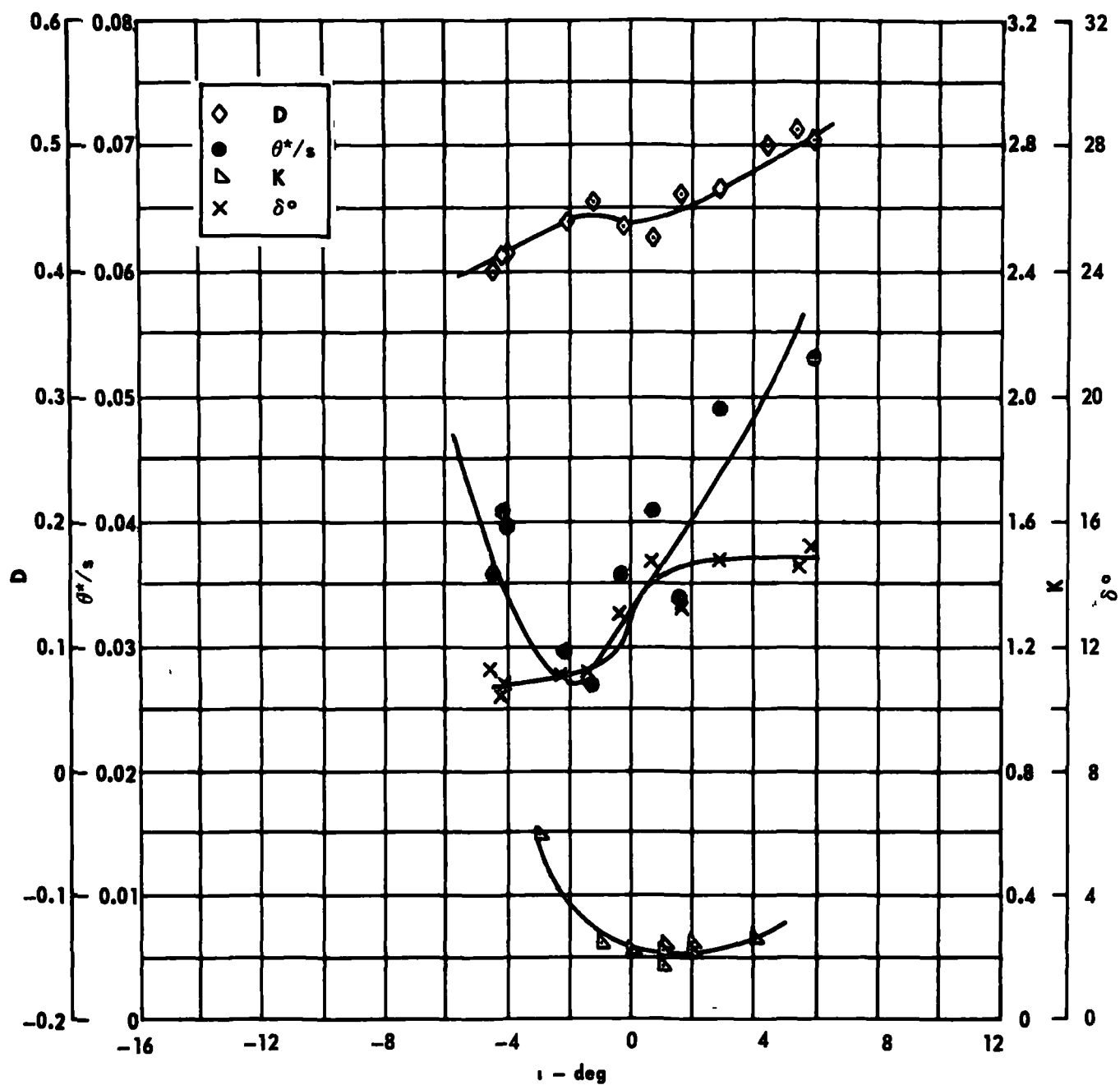


Figure 19. - Cascade characteristics as functions of incidence.



Cascade configuration $\beta_{1N} = 60, \sigma = 1.50$

M606 profile $\phi = 30, t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 19. - Concluded.

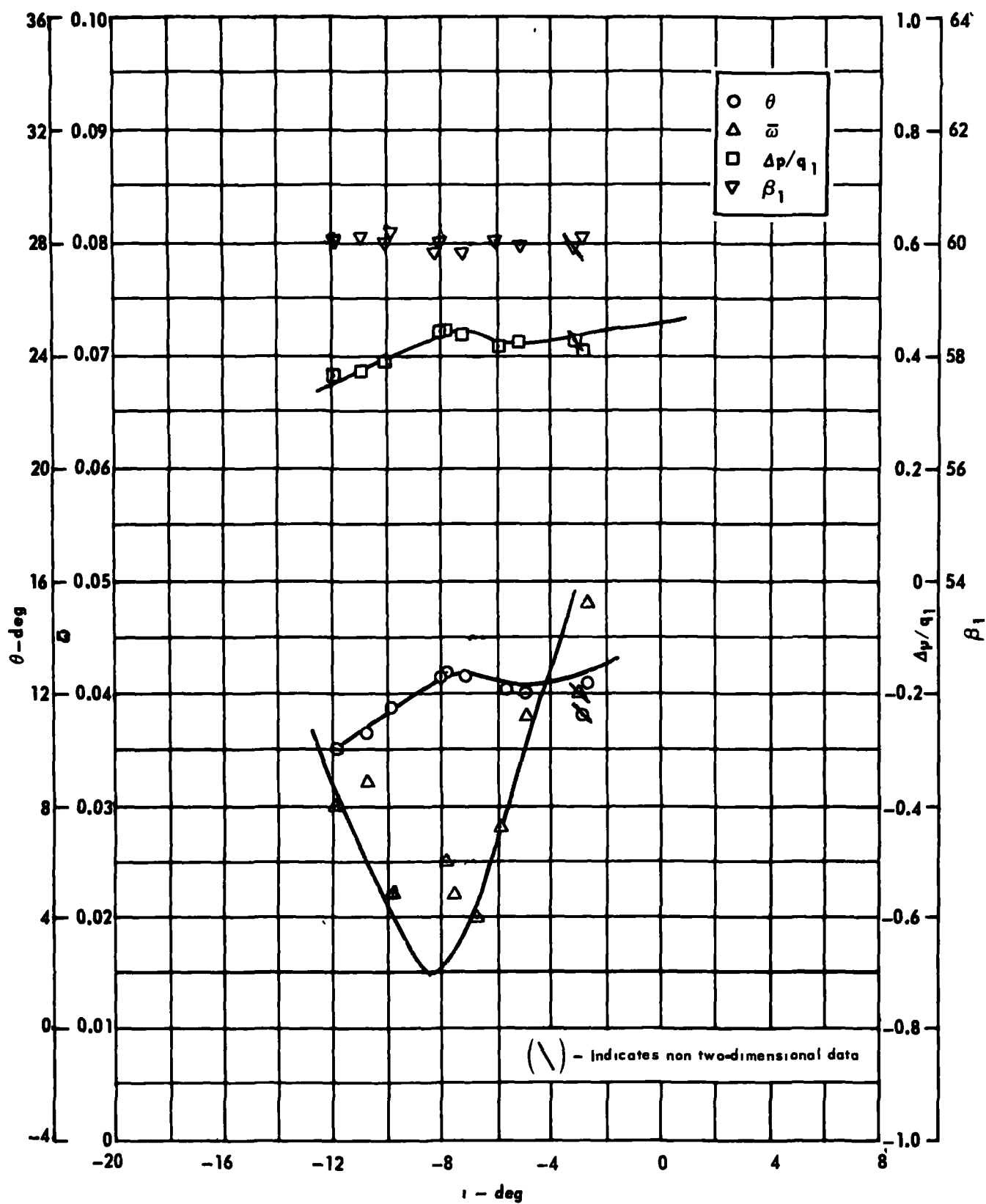
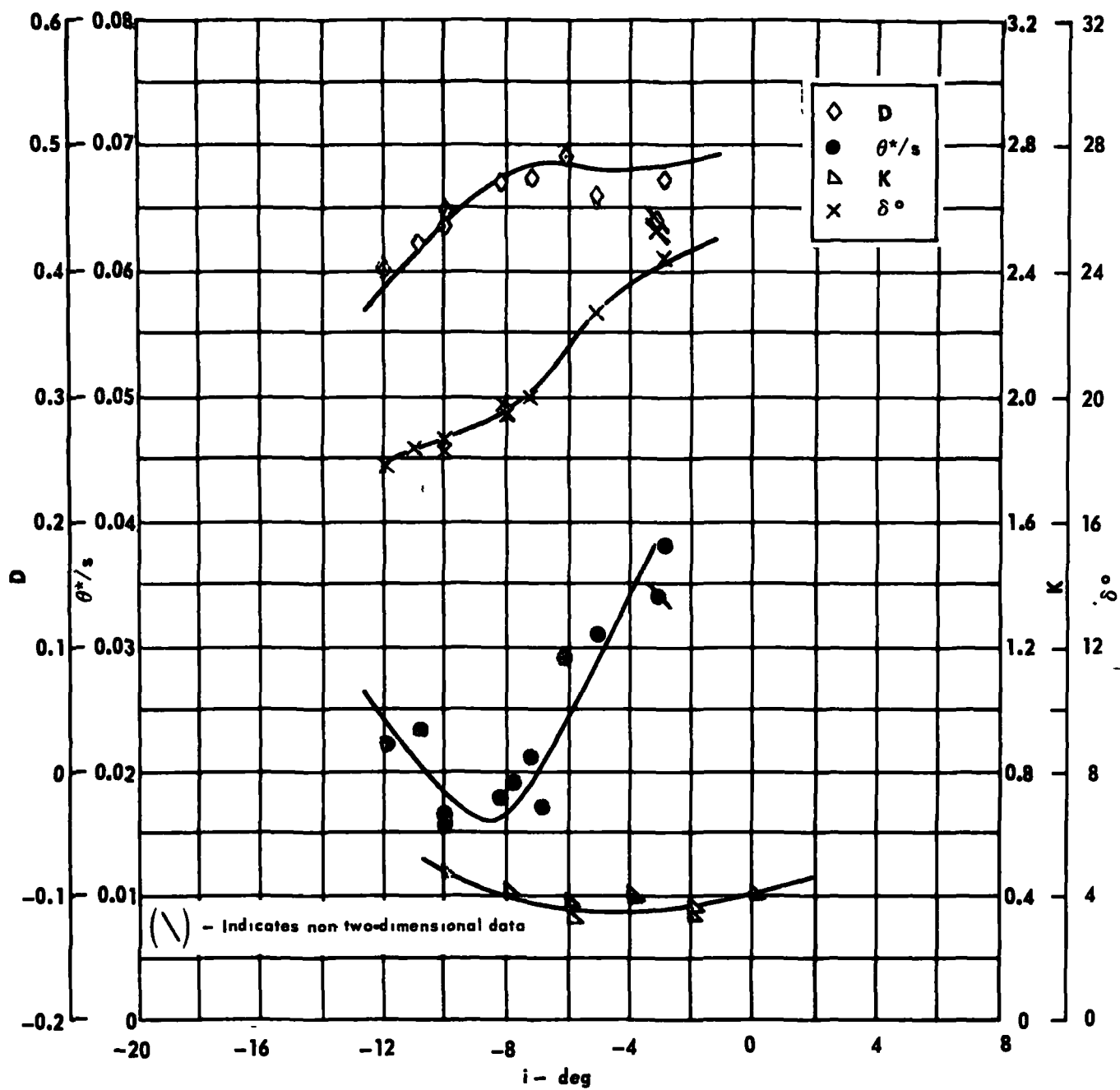


Figure 20. - Cascade characteristics as functions of incidence.

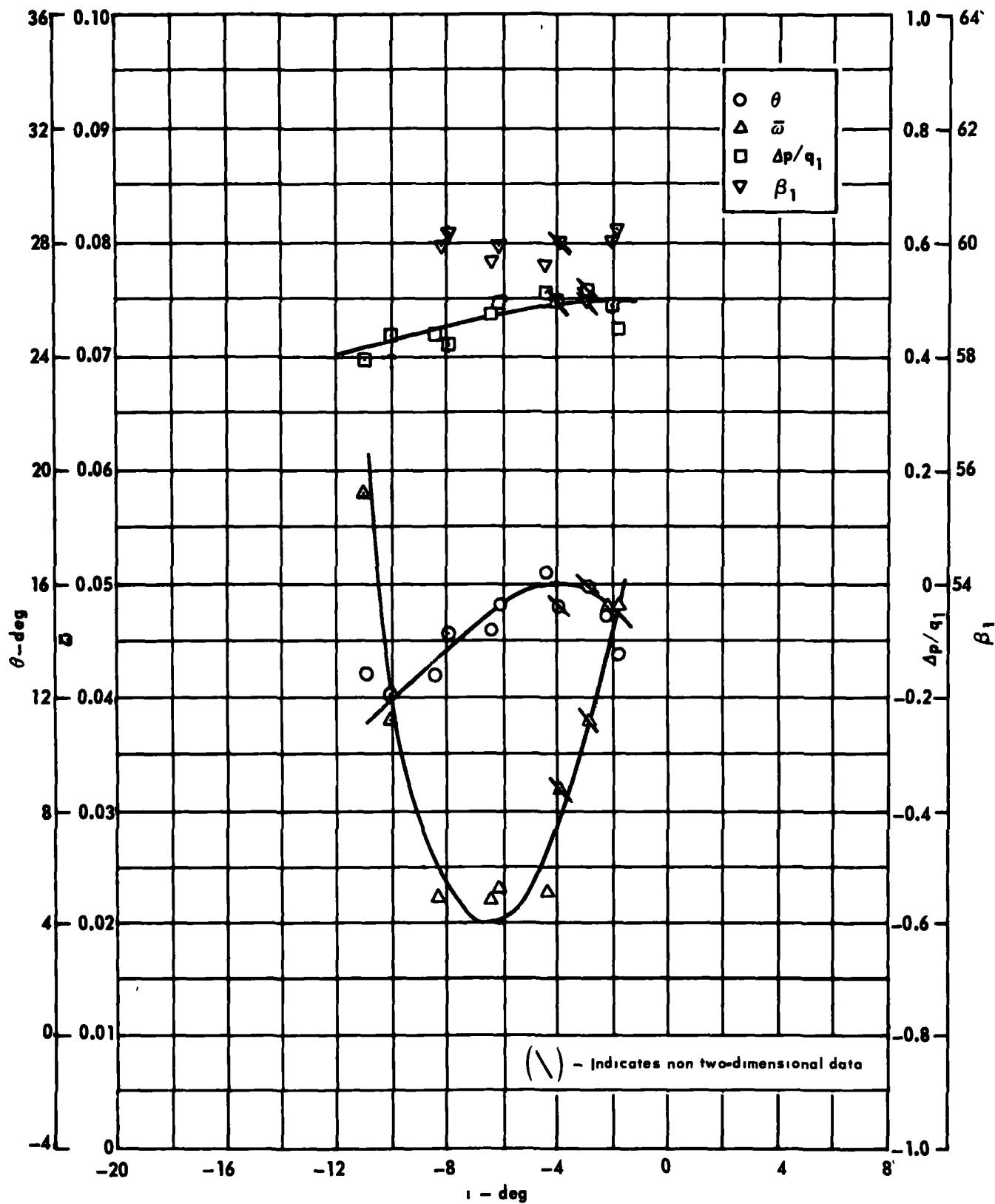


Cascade configuration $\beta_{1N} = 60, \sigma = 0.75$

M606 profile: $\phi = 40, t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 20. - Concluded.



Cascade configuration $\beta_{1N} = 60$, $\sigma = 1.00$

M606 profile $\phi = 40$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 21. - Cascade characteristics as functions of incidence.

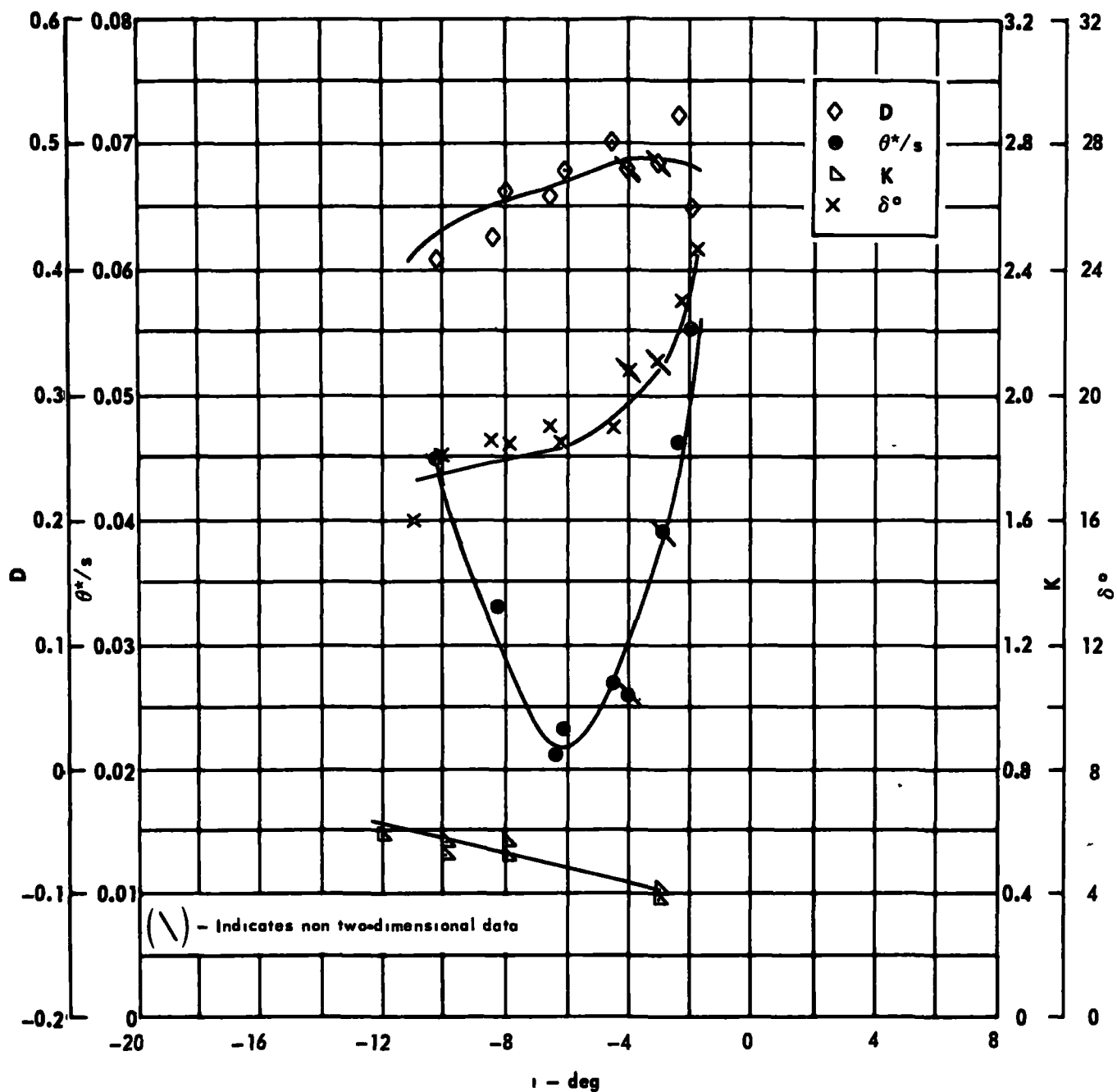


Figure 21. - Concluded.

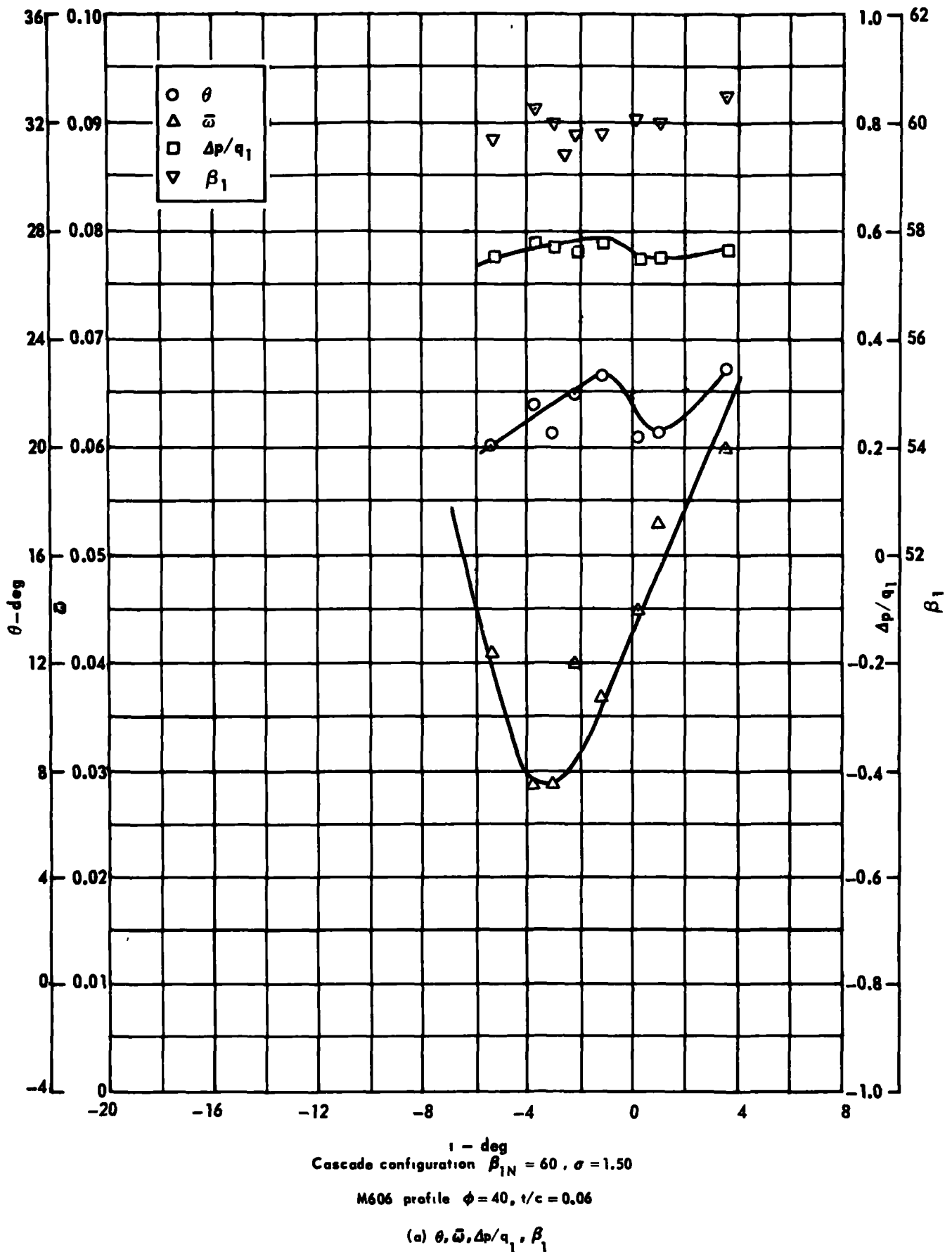
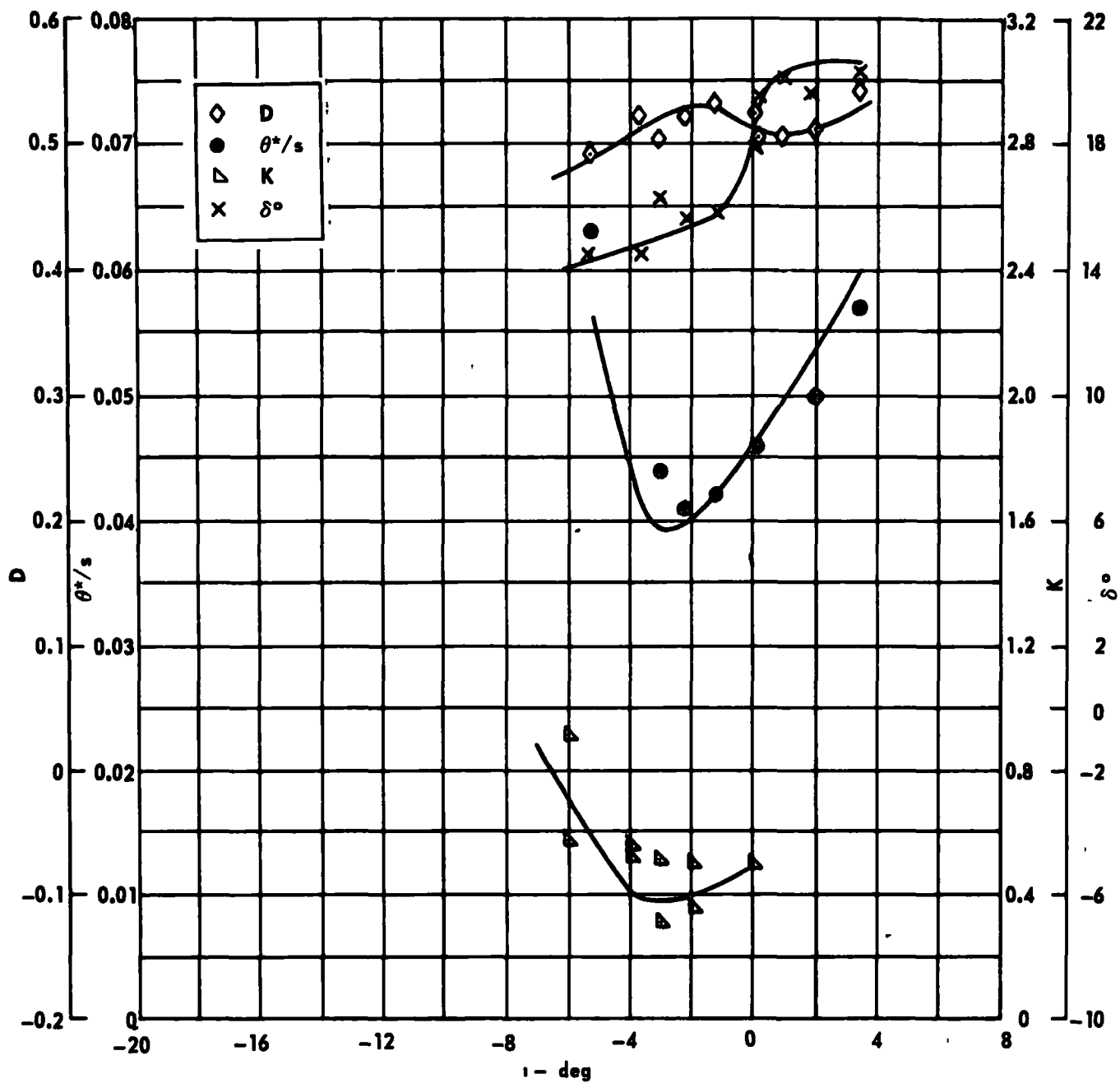


Figure 22. - Cascade characteristics as functions of incidence.

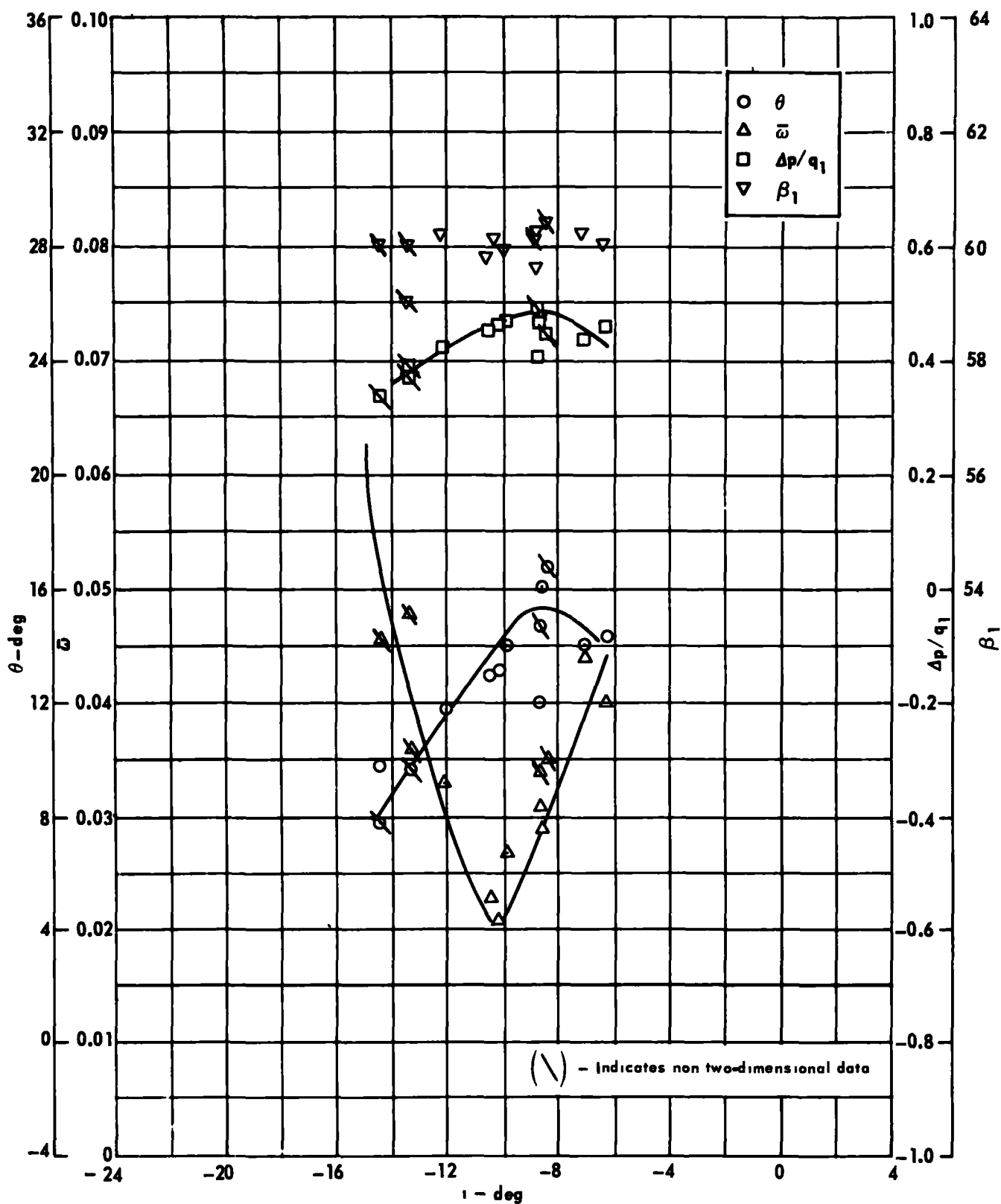


Cascade configuration $\beta_{1N} = 60, \sigma = 1.50$

M606 profile : $\phi = 40, t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 22. - Concluded.

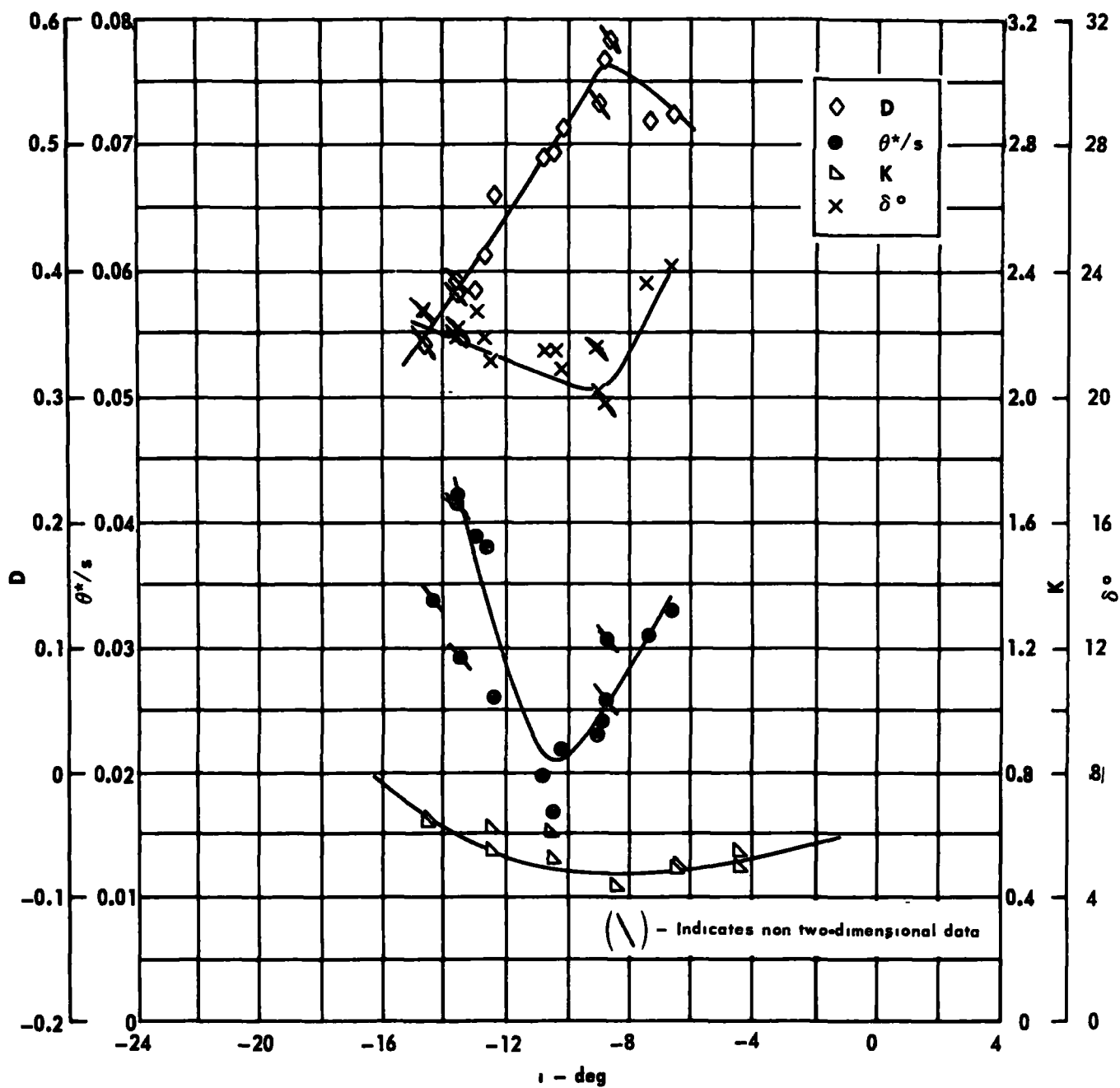


Cascade configuration $\beta_{1N} = 60$, $\sigma = 0.75$

M606 profile $\phi = 45$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 23 . - Cascade characteristics as functions of incidence.



Cascade configuration $\beta_{1N} = 60$, $\sigma = 0.75$

M606 profile $\phi = 45$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 23. - Concluded.

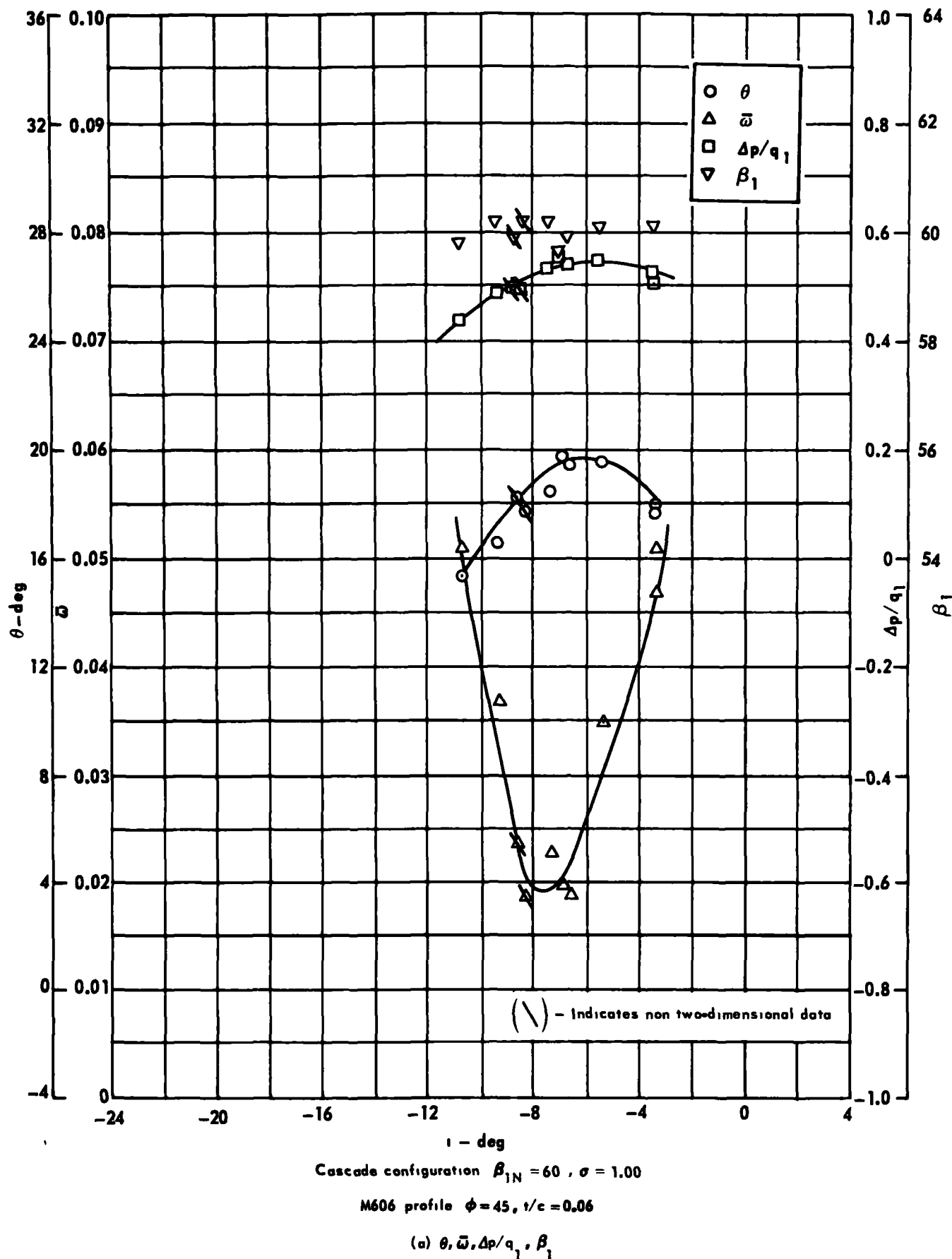
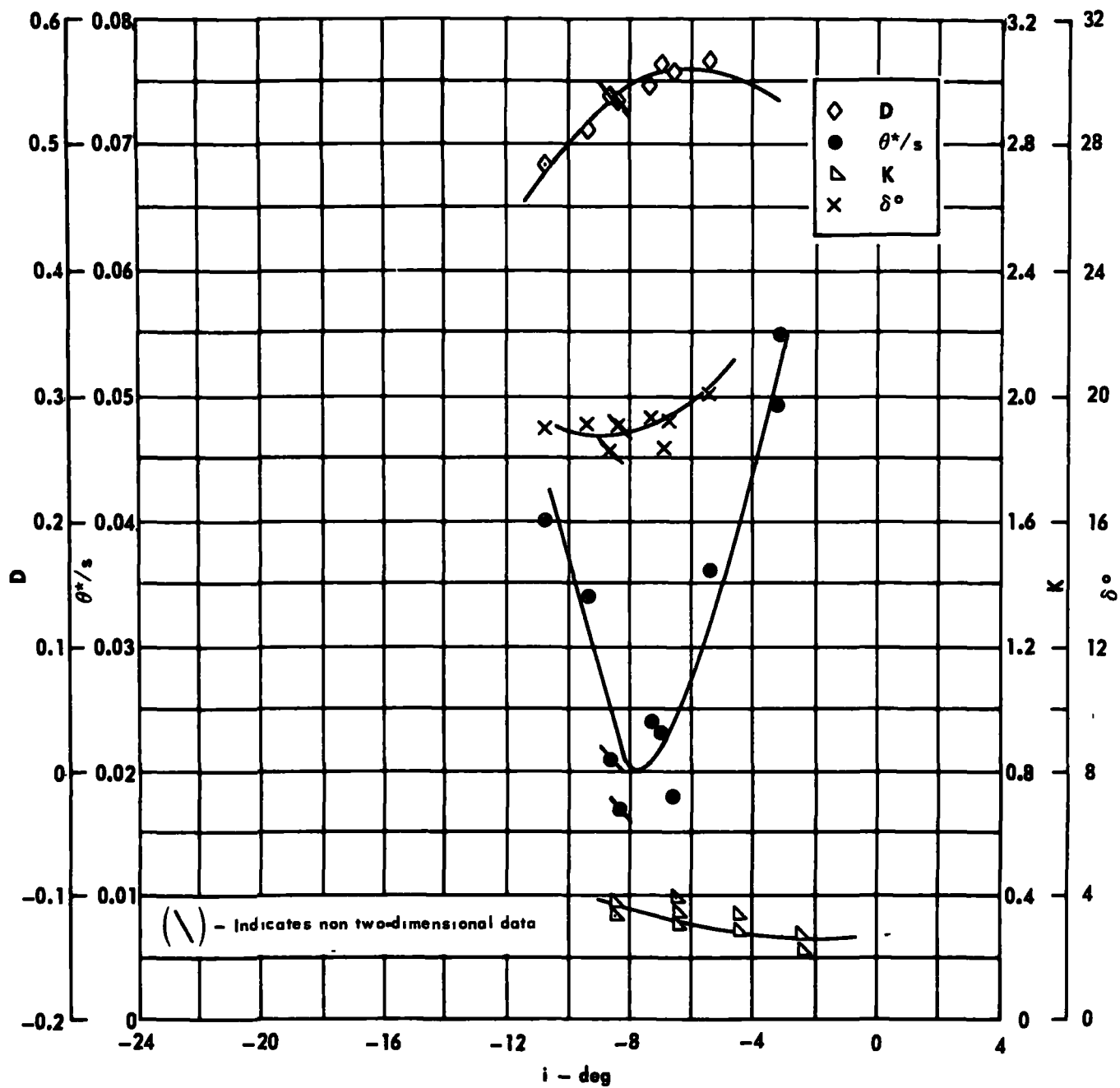


Figure 24. - Cascade characteristics as functions of incidence.

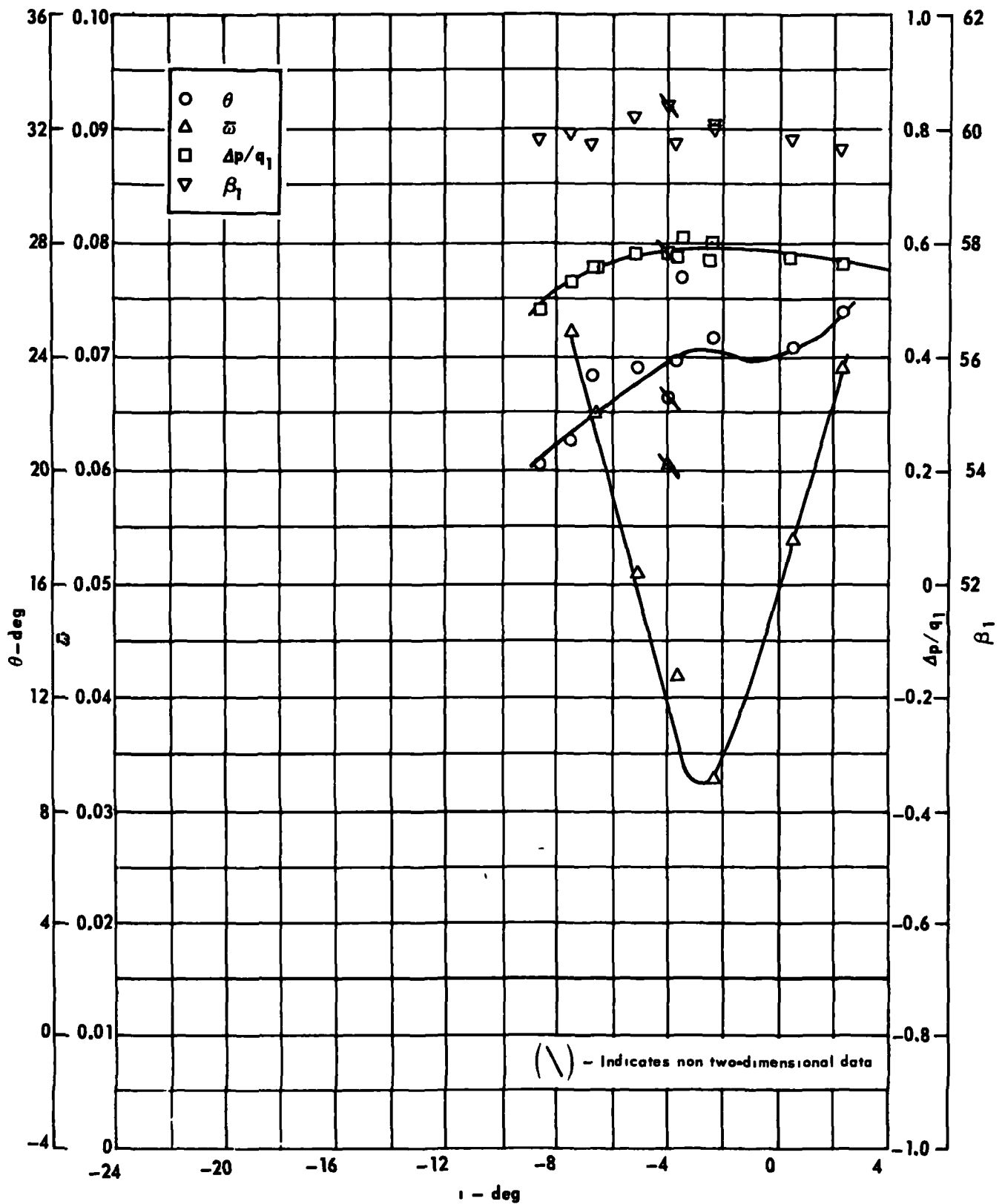


Cascade configuration $\beta_{1N} = 60$, $\sigma = 1.00$

M606 profile $\phi = 45$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 24. - Concluded.

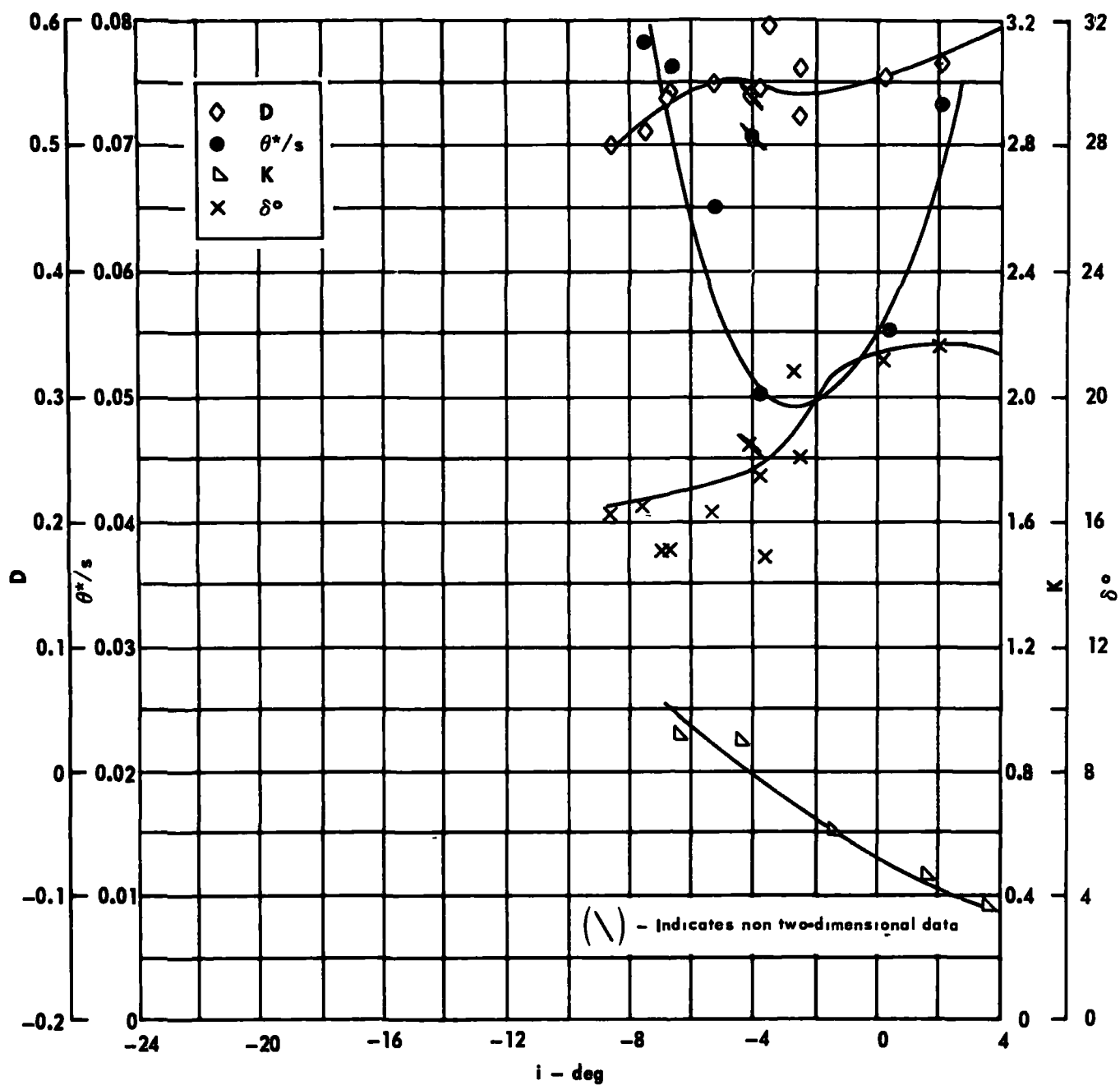


Cascade configuration $\beta_{1N} = 60$, $\sigma = 1.50$

M606 profile $\phi = 45$, $t/c = 0.06$

(a) $\theta, \omega, \Delta p/q_1, \beta_1$

Figure 25. - Cascade characteristics as functions of incidence.



Cascade configuration $\beta_{1N} = 60$, $\sigma = 1.50$

M606 profile $\phi = 45$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 25 . - Concluded.

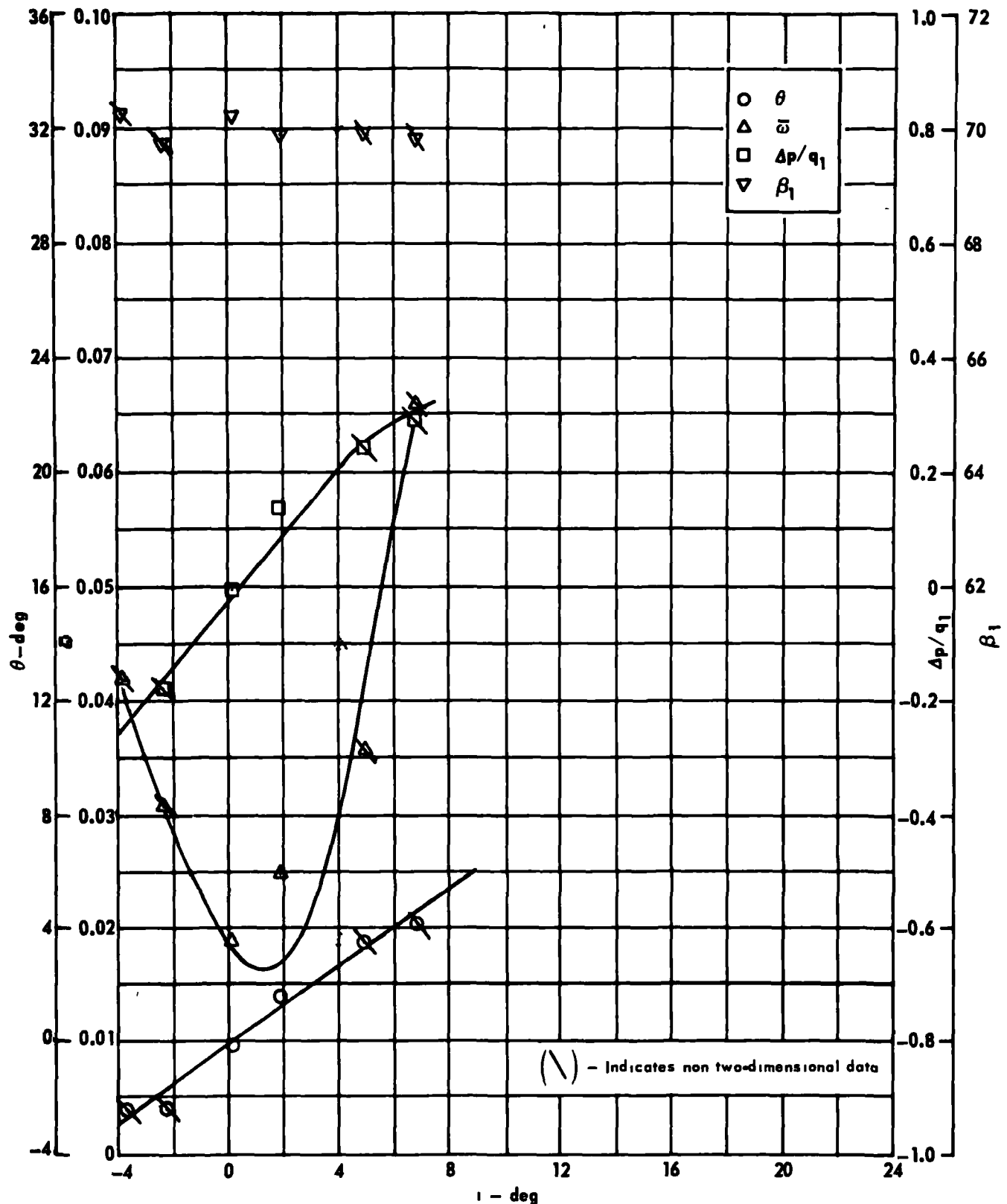
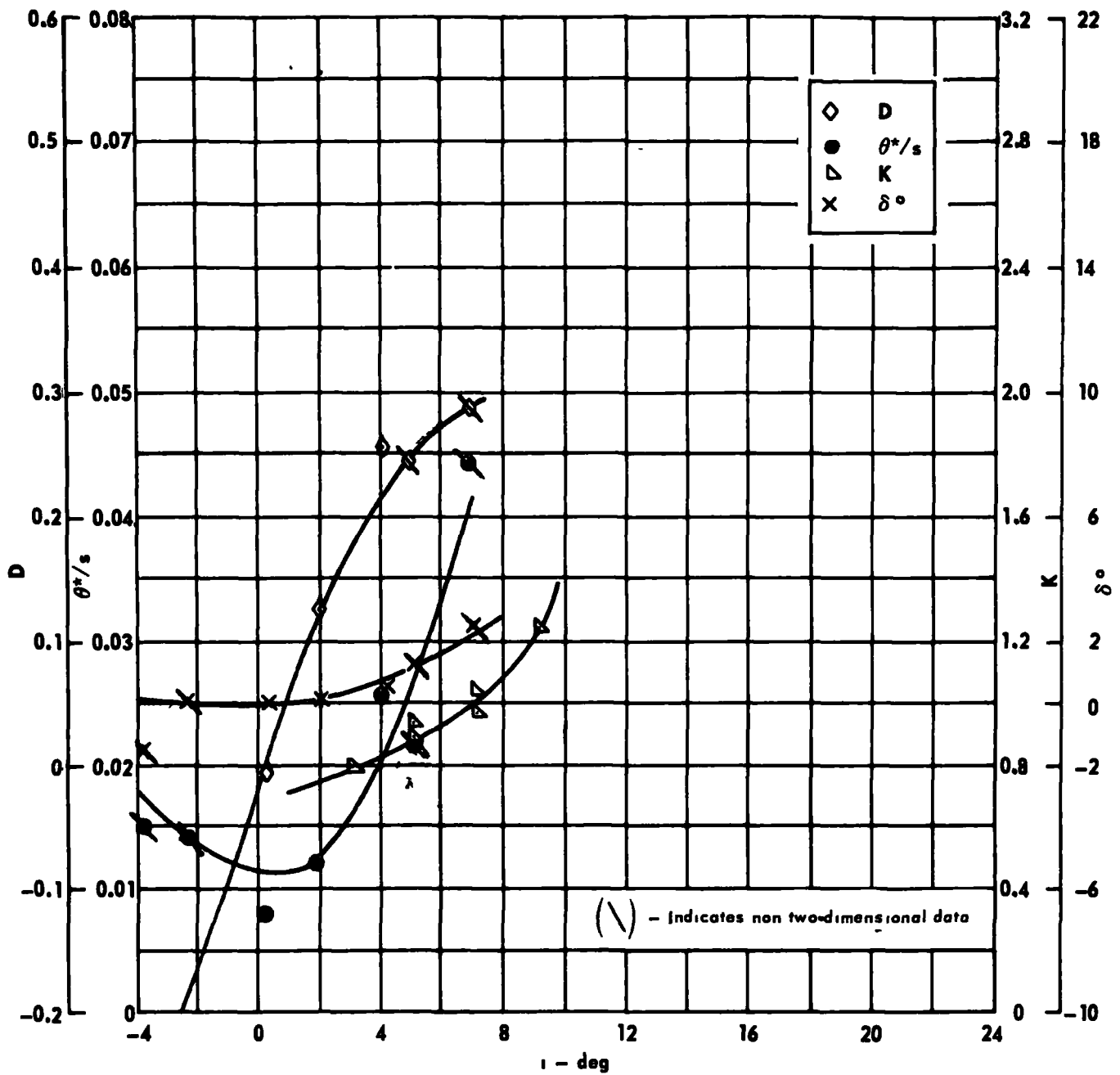


Figure 26. - Cascade characteristics as functions of incidence.

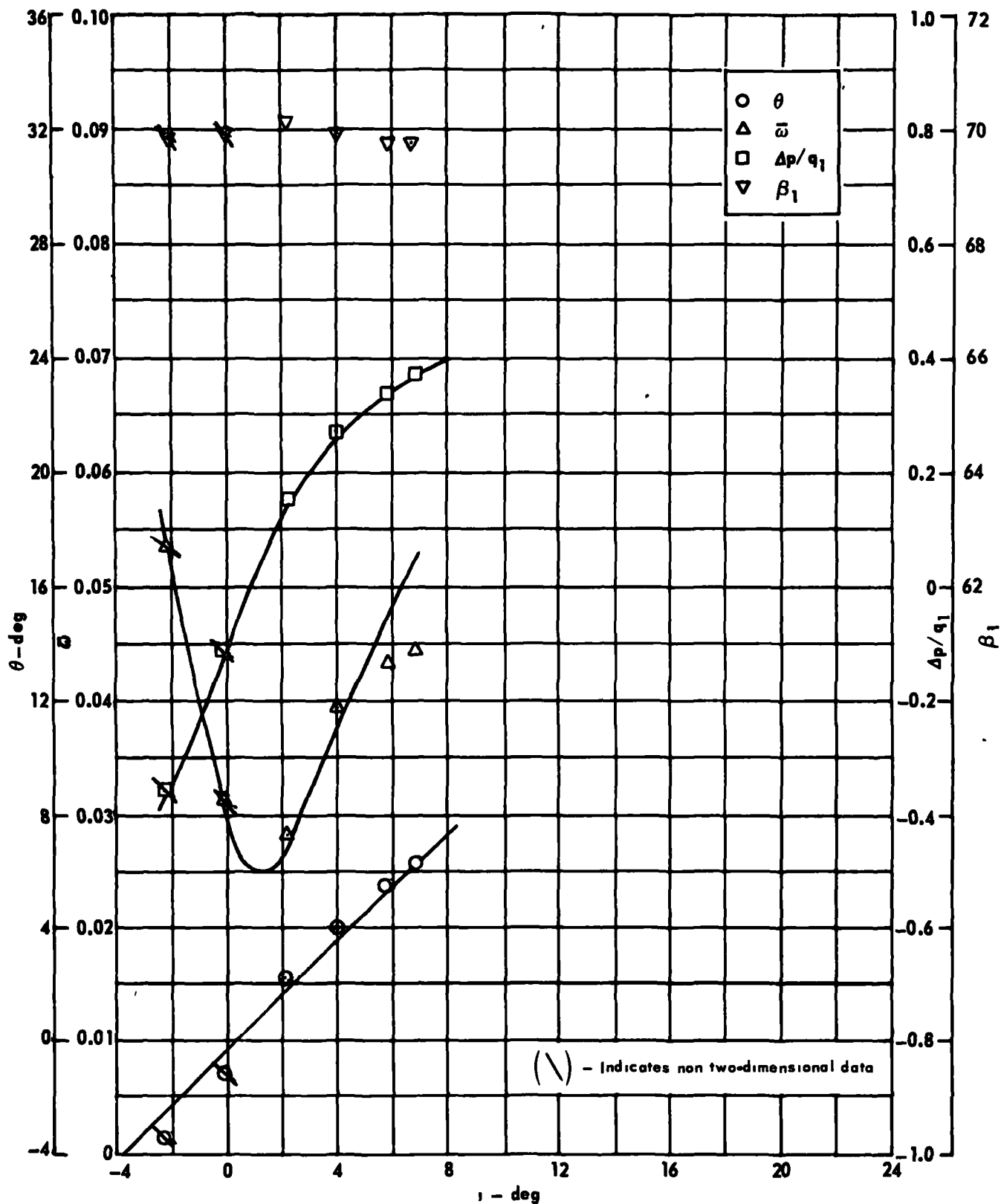


Cascade configuration $\beta_{1N} = 70$, $\sigma = 0.75$

M606 profile, $\phi = 0$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 26. - Concluded.

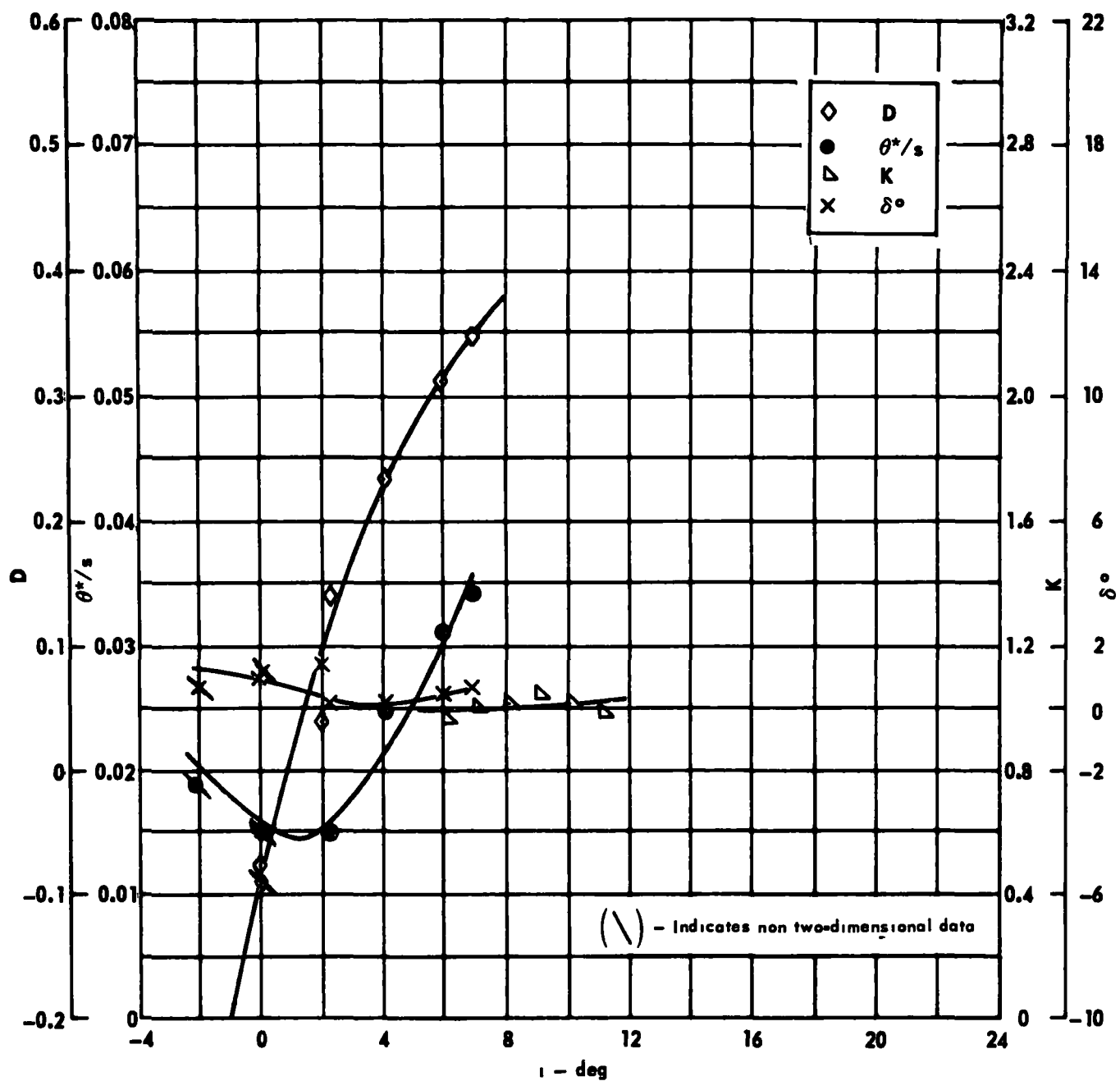


Cascade configuration $\beta_{1N} = 70$, $\sigma = 1.00$

M606 profile $\phi = 0$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 27. - Cascade characteristics as functions of incidence.

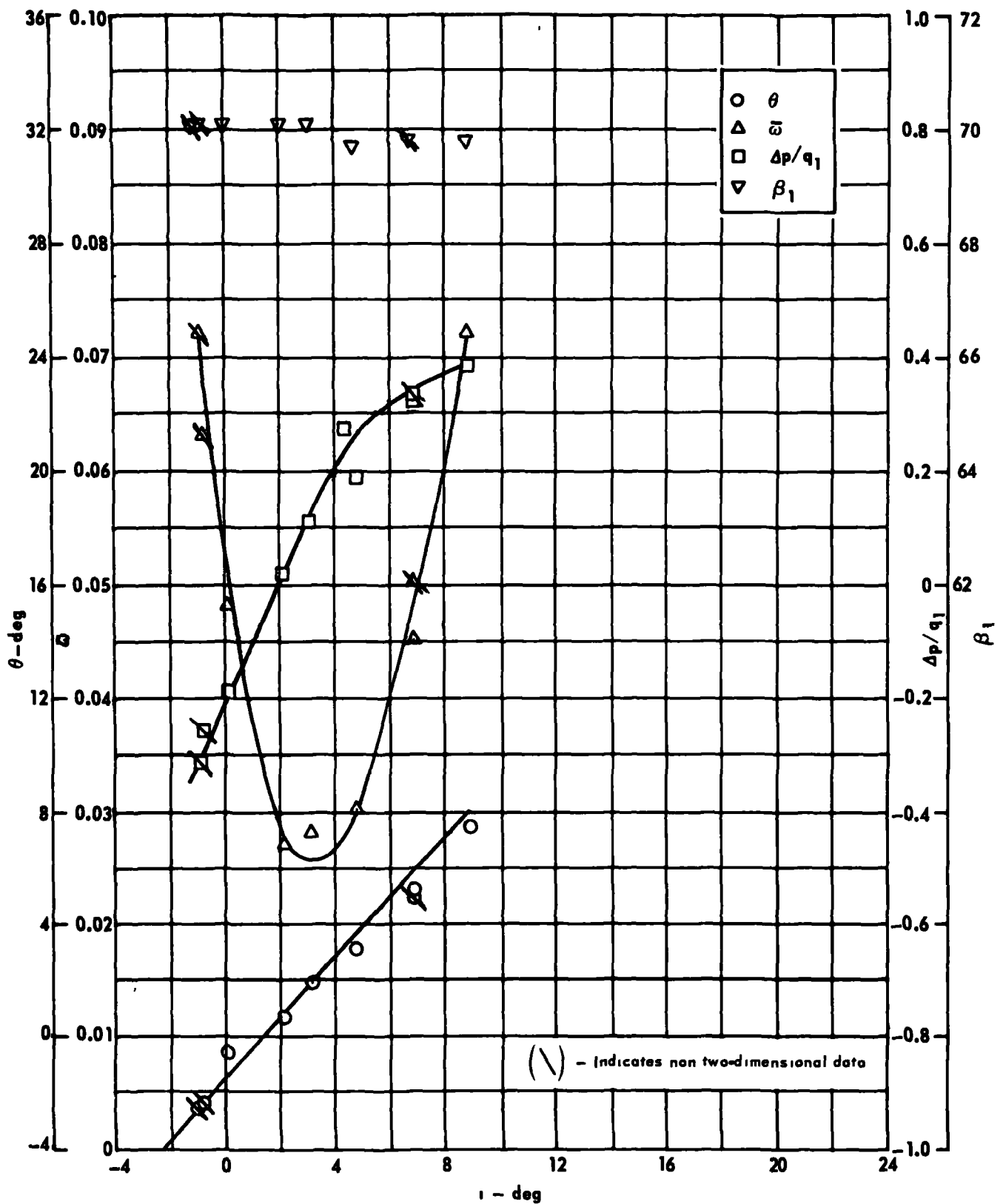


Cascade configuration $\beta_{1N} = 70, \sigma = 1.00$

M606 profile : $\phi = 0, t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 27. - Concluded.

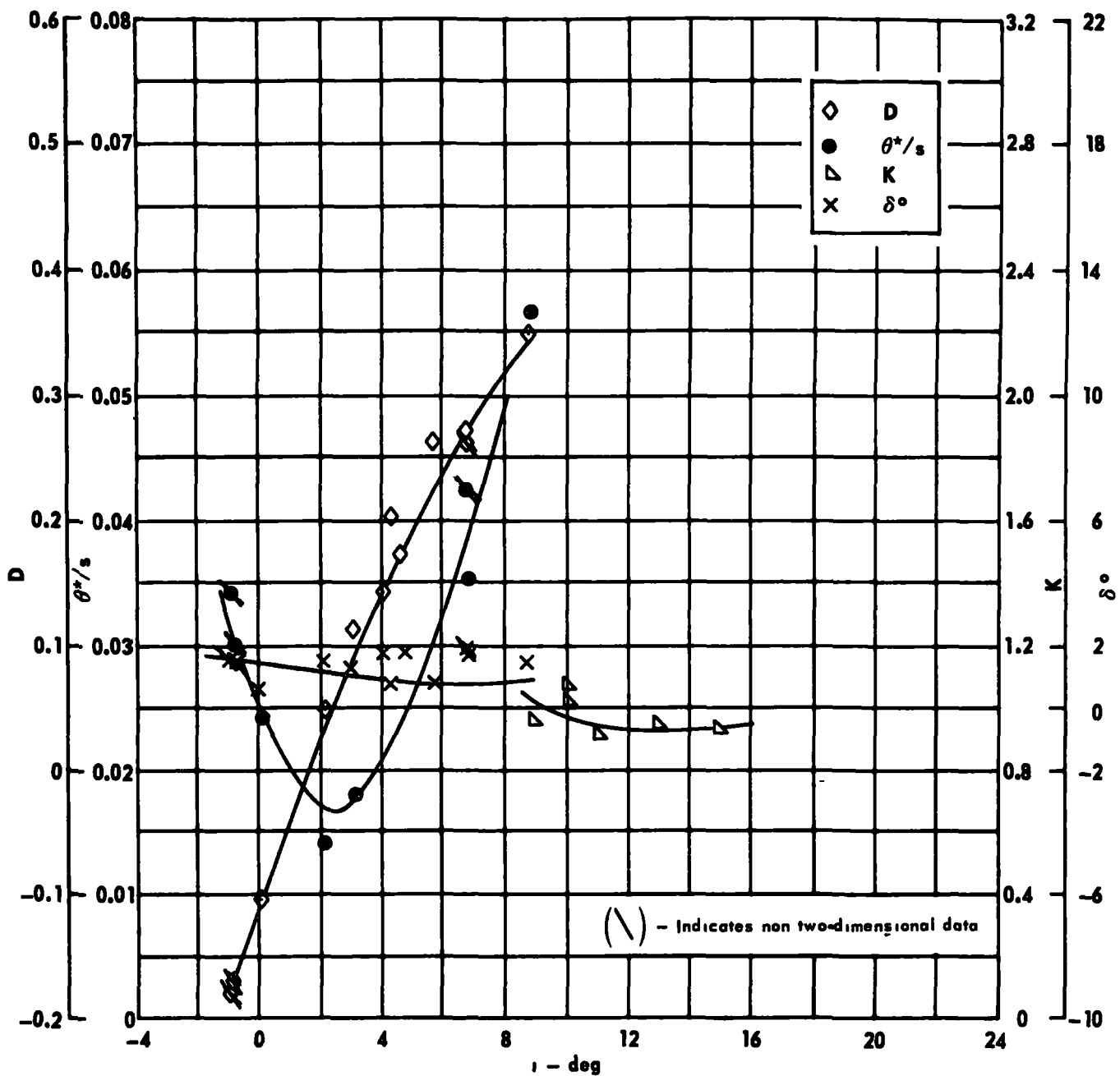


Cascade configuration $\beta_{1N} = 70$, $\sigma = 1.50$

M606 profile $\phi = 0$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 28. - Cascade characteristics as functions of incidence.

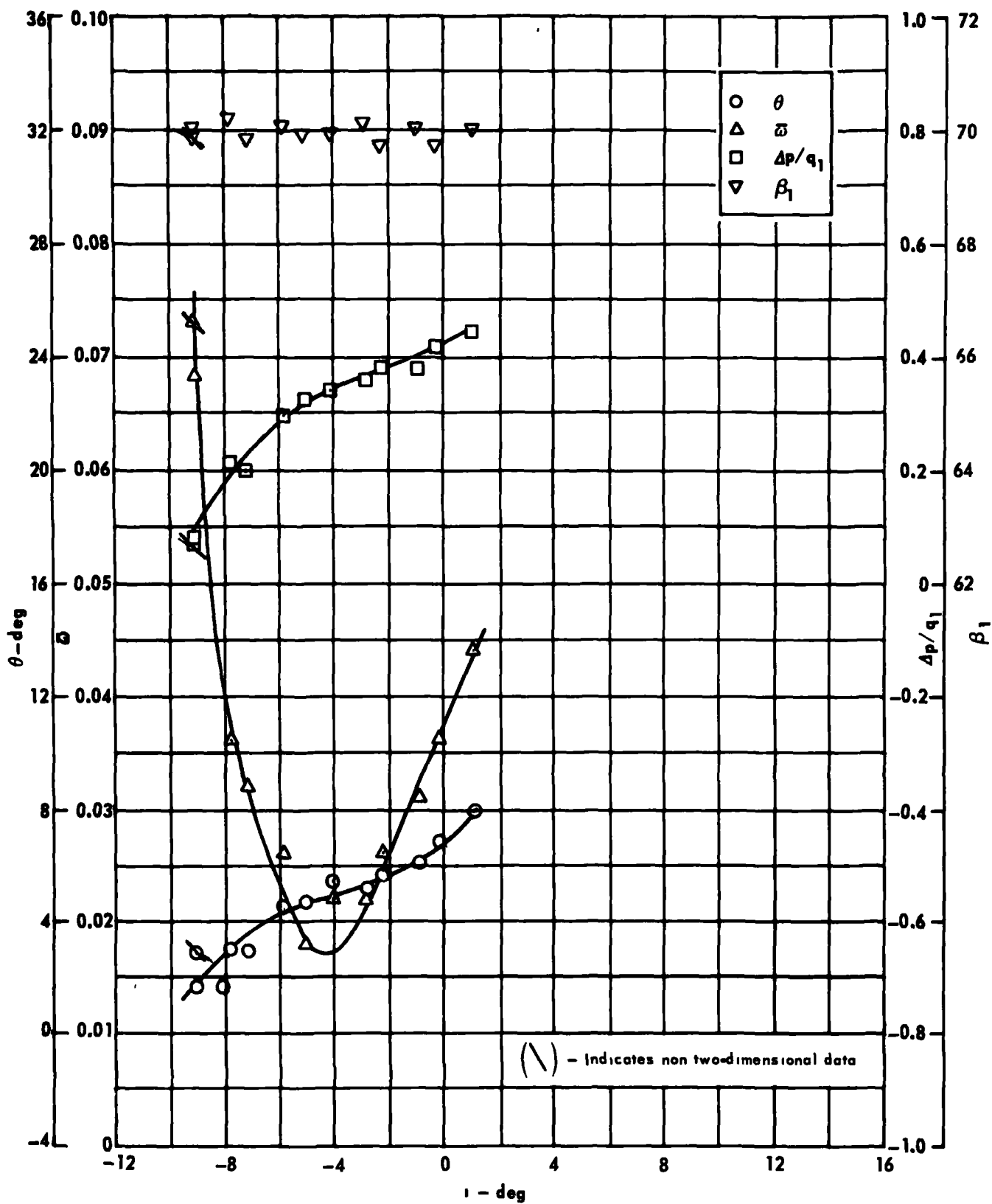


Cascade configuration $\beta_{1N} = 70$, $\sigma = 1.50$

M606 profile $\phi = 0$, $t/c = 0.06$

(b) D, θ^*/s , K, δ°

Figure 28. - Concluded.



Cascade configuration $\beta_{1N} = 70$, $\sigma = 0.75$

M606 profile $\phi = 20$, $t/c = 0.06$

(a) $\theta, \omega, \Delta p/q_1, \beta_1$

Figure 29. - Cascade characteristics as functions of incidence.

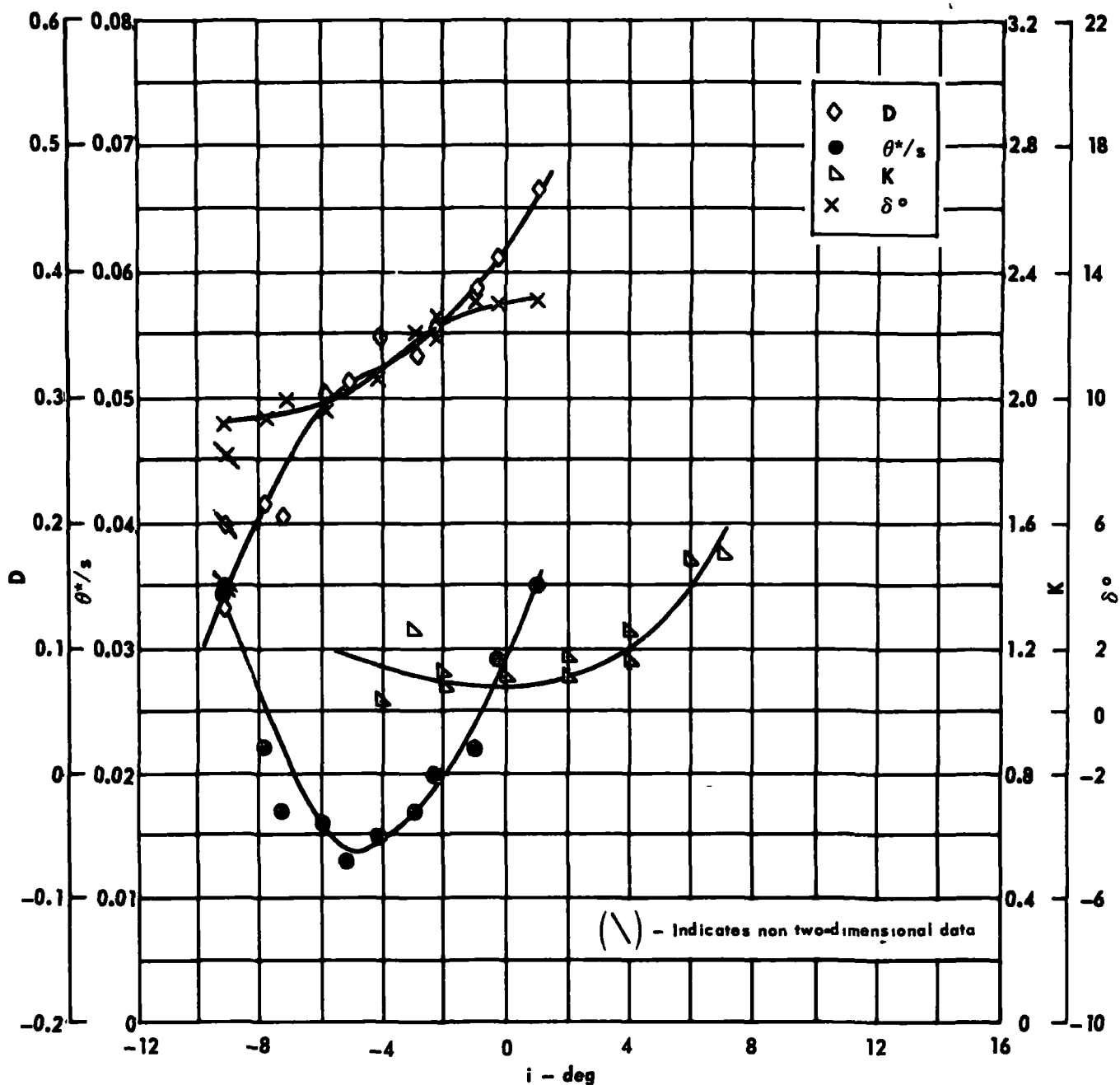
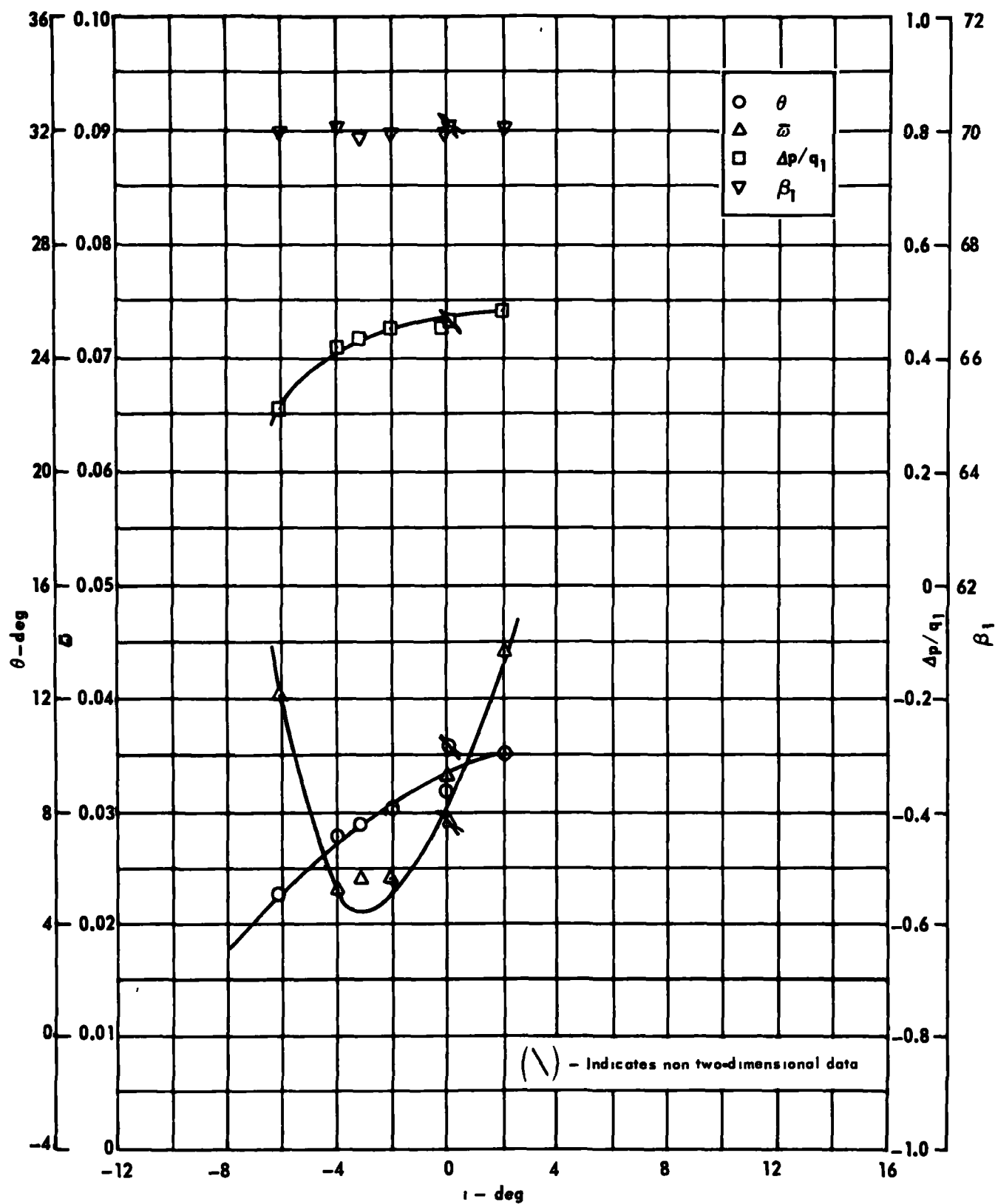


Figure 29. - Concluded.

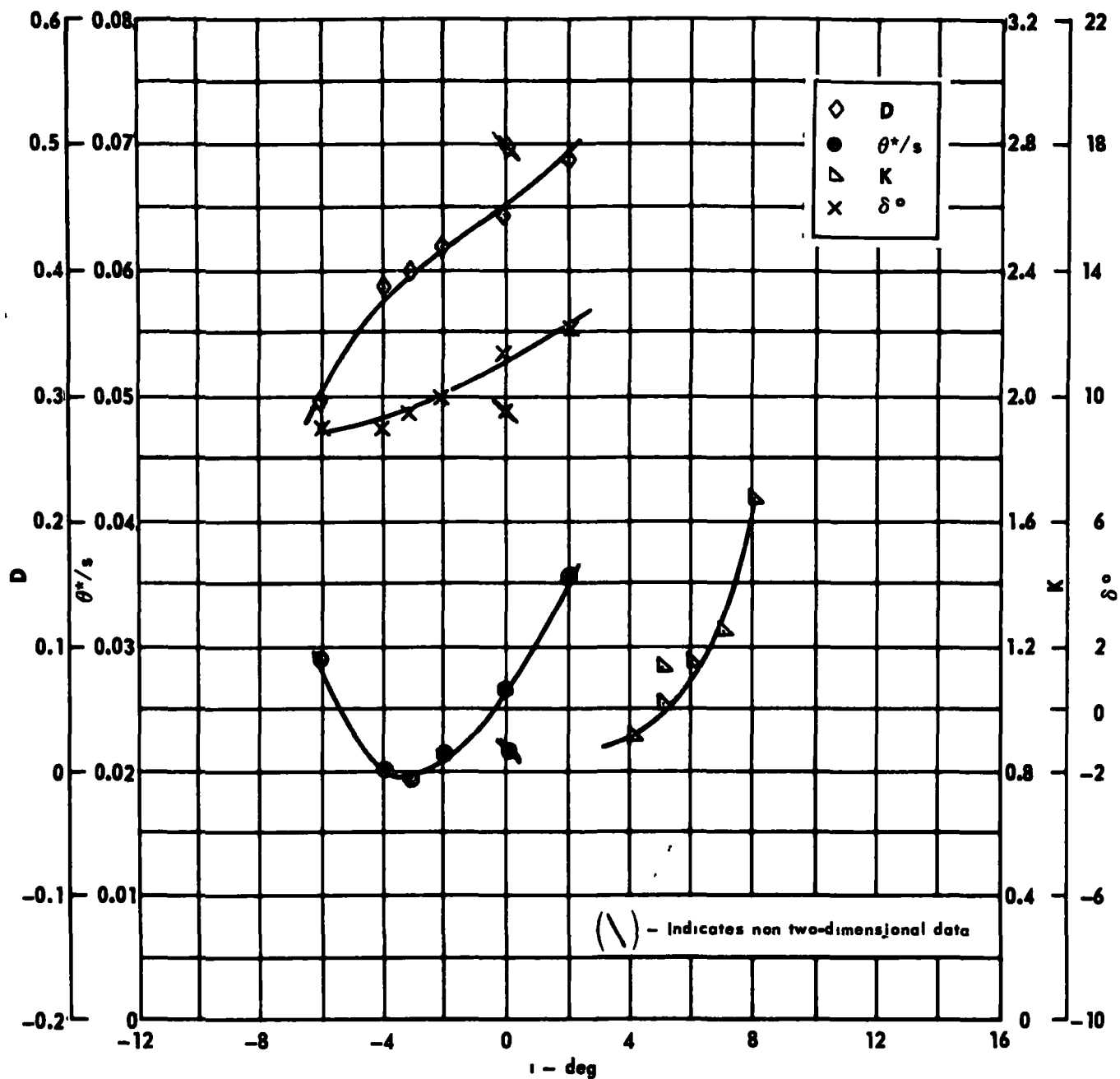


Cascade configuration $\beta_{1N} = 70$, $\sigma = 1.00$

M606 profile $\phi = 20$, $t/c = 0.06$

(a) $\theta, \omega, \Delta p/q_1, \beta_1$

Figure 30. - Cascade characteristics as functions of incidence.

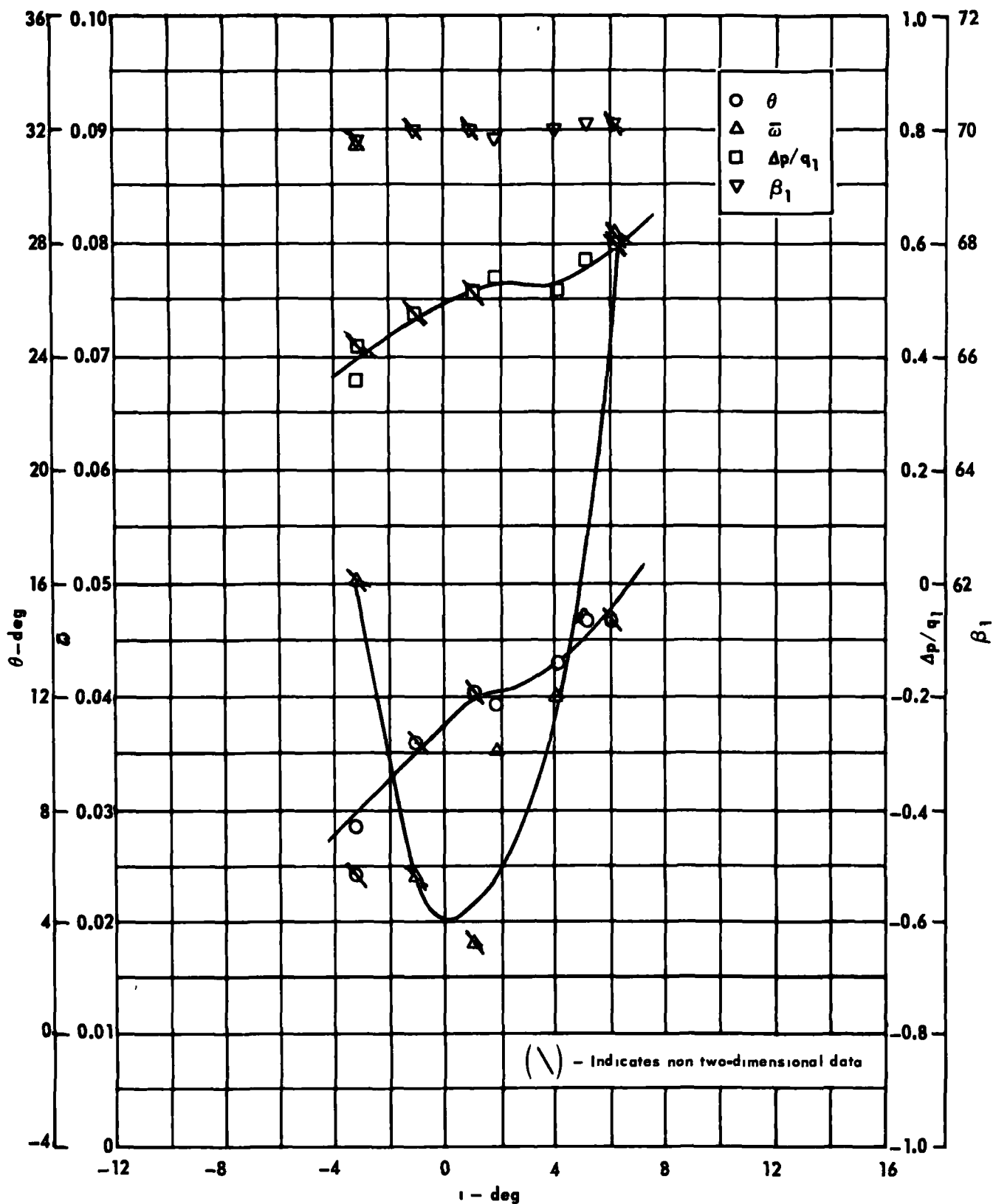


Cascade configuration $\beta_{1N} = 70$, $\sigma = 1.00$

M606 profile $\phi = 20$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 30. - Concluded.

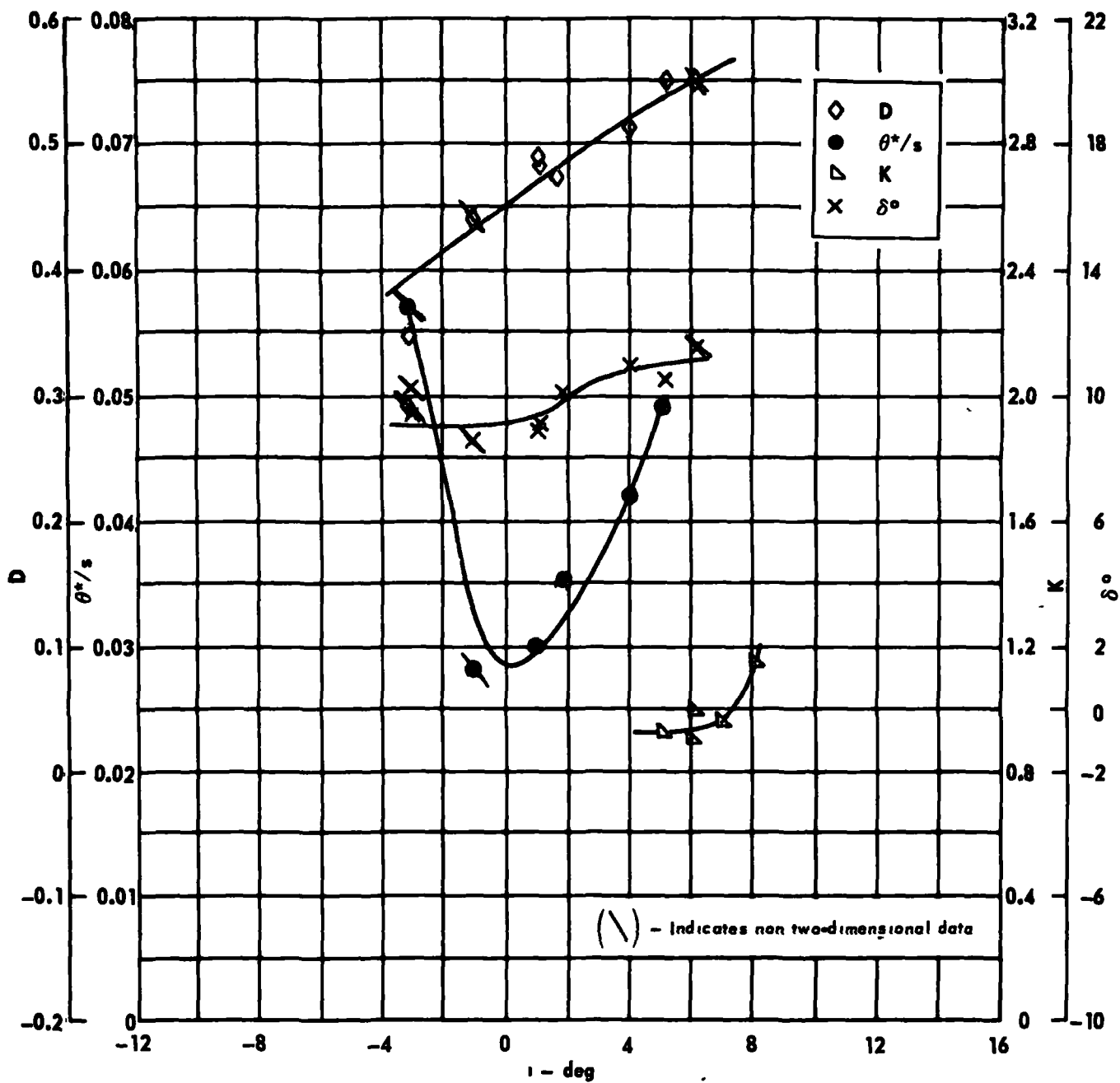


Cascade configuration $\beta_{1N} = 70, \sigma = 1.50$

M606 profile $\phi = 20, t/c = 0.06$

(a) $\theta, \omega, \Delta p/q_1, \beta_1$

Figure 31. - Cascade characteristics as functions of incidence.



Cascade configuration $\beta_N = 70$, $\sigma = 1.50$

M606 profile $\phi = 20$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 31. - Concluded.

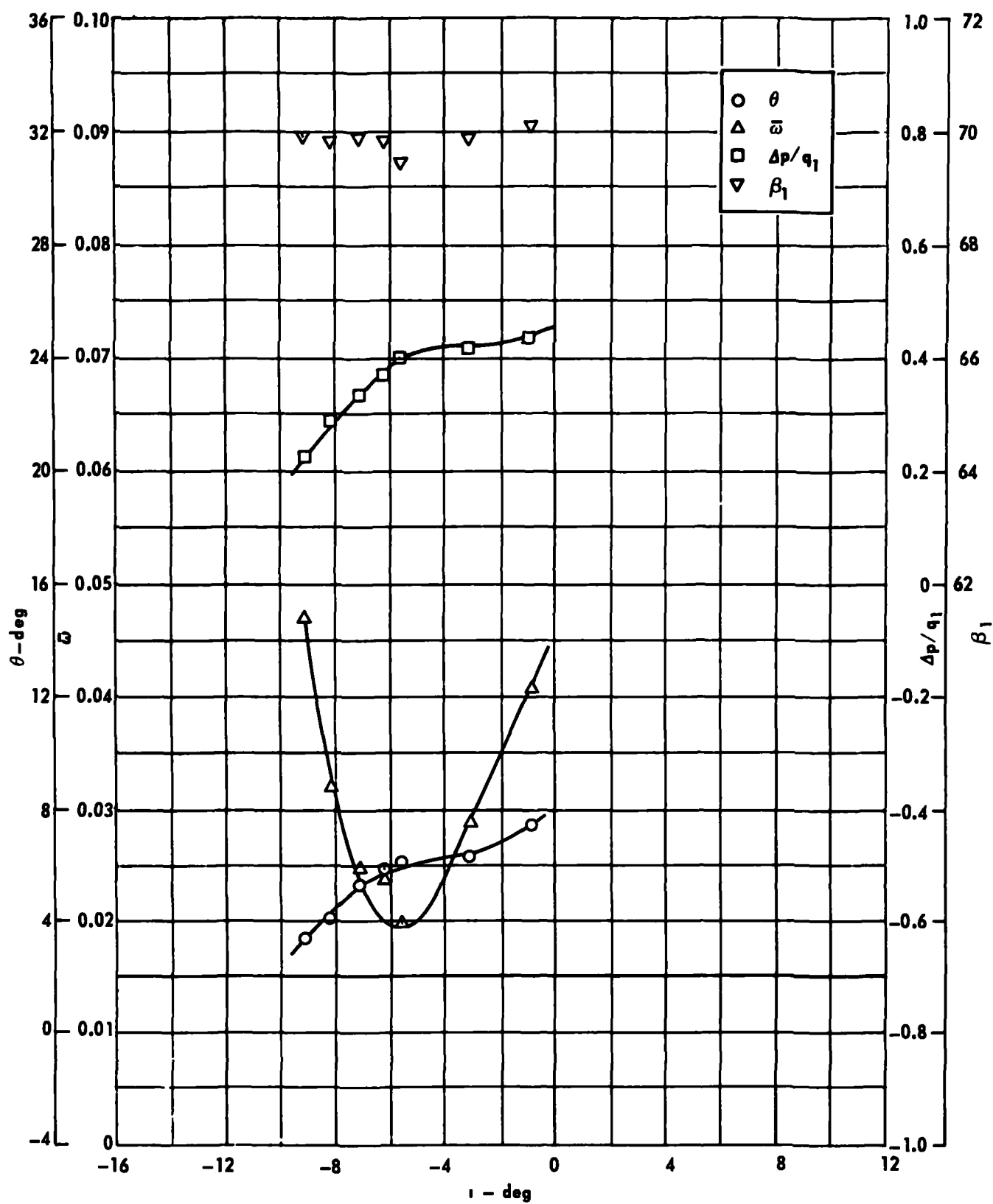
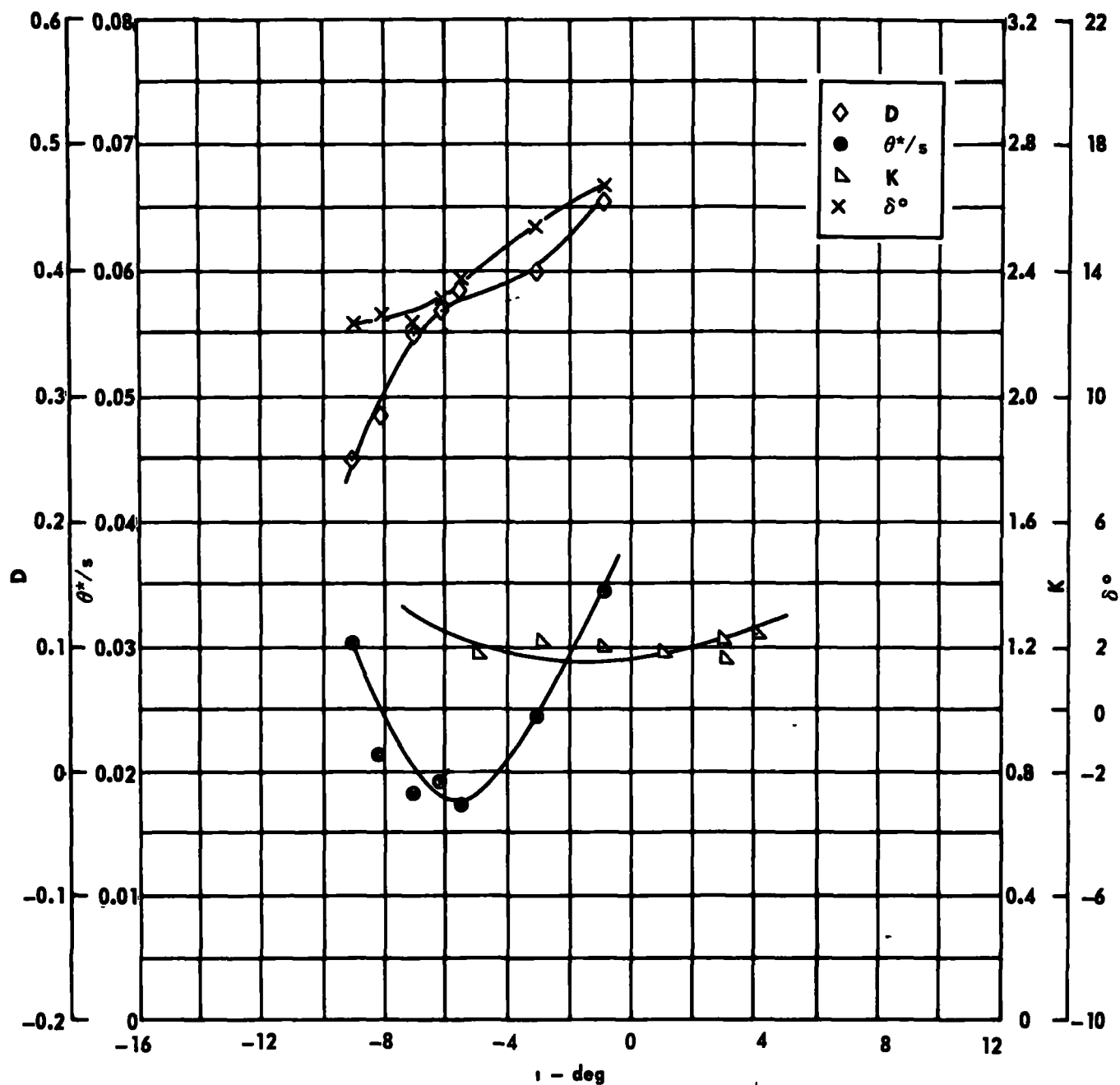


Figure 32. - Cascade characteristics as functions of incidence.

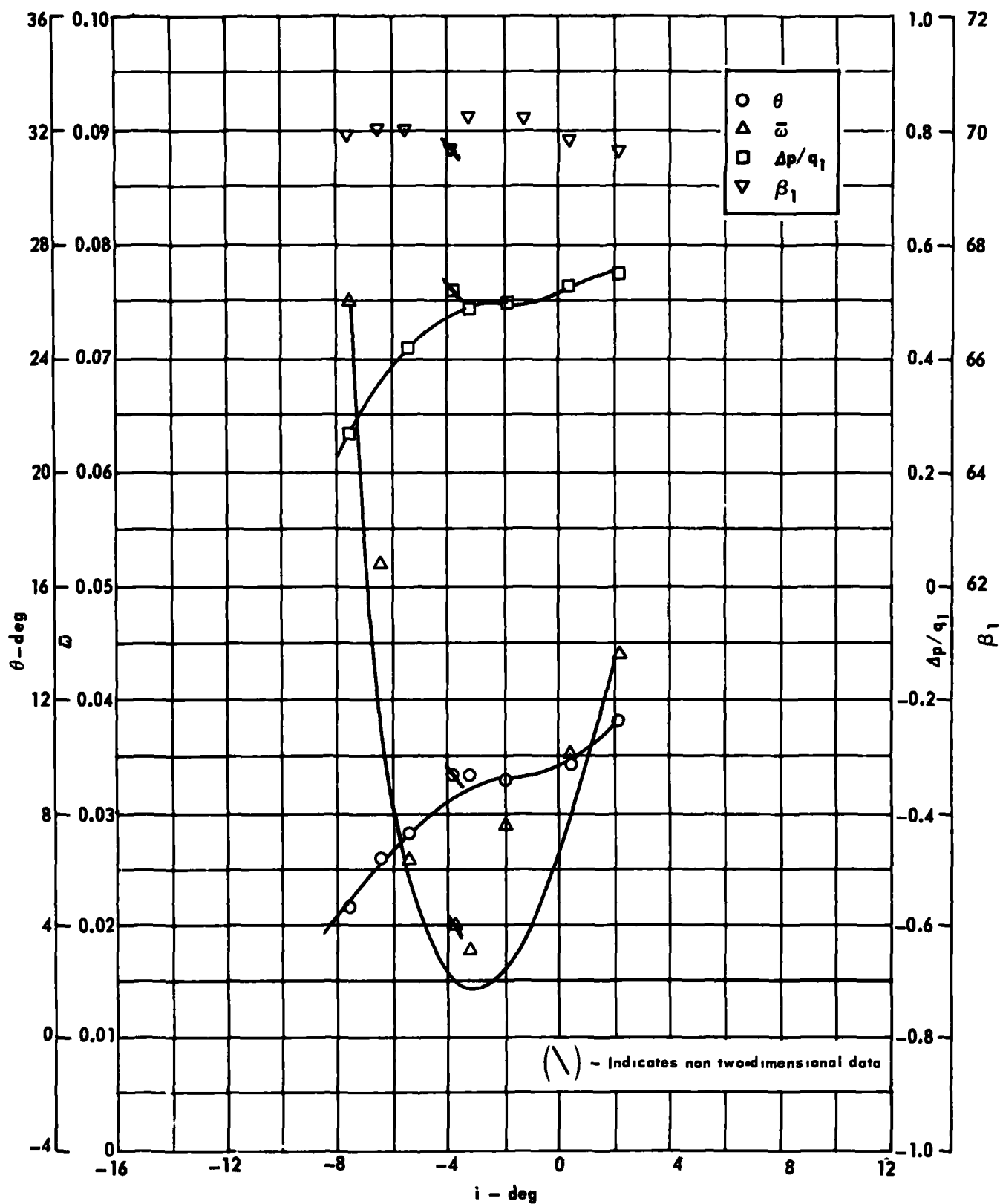


Cascade configuration $\beta_{1N} = 70$, $\sigma = 0.75$

M606 profile $\phi = 25$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 32. - Concluded.

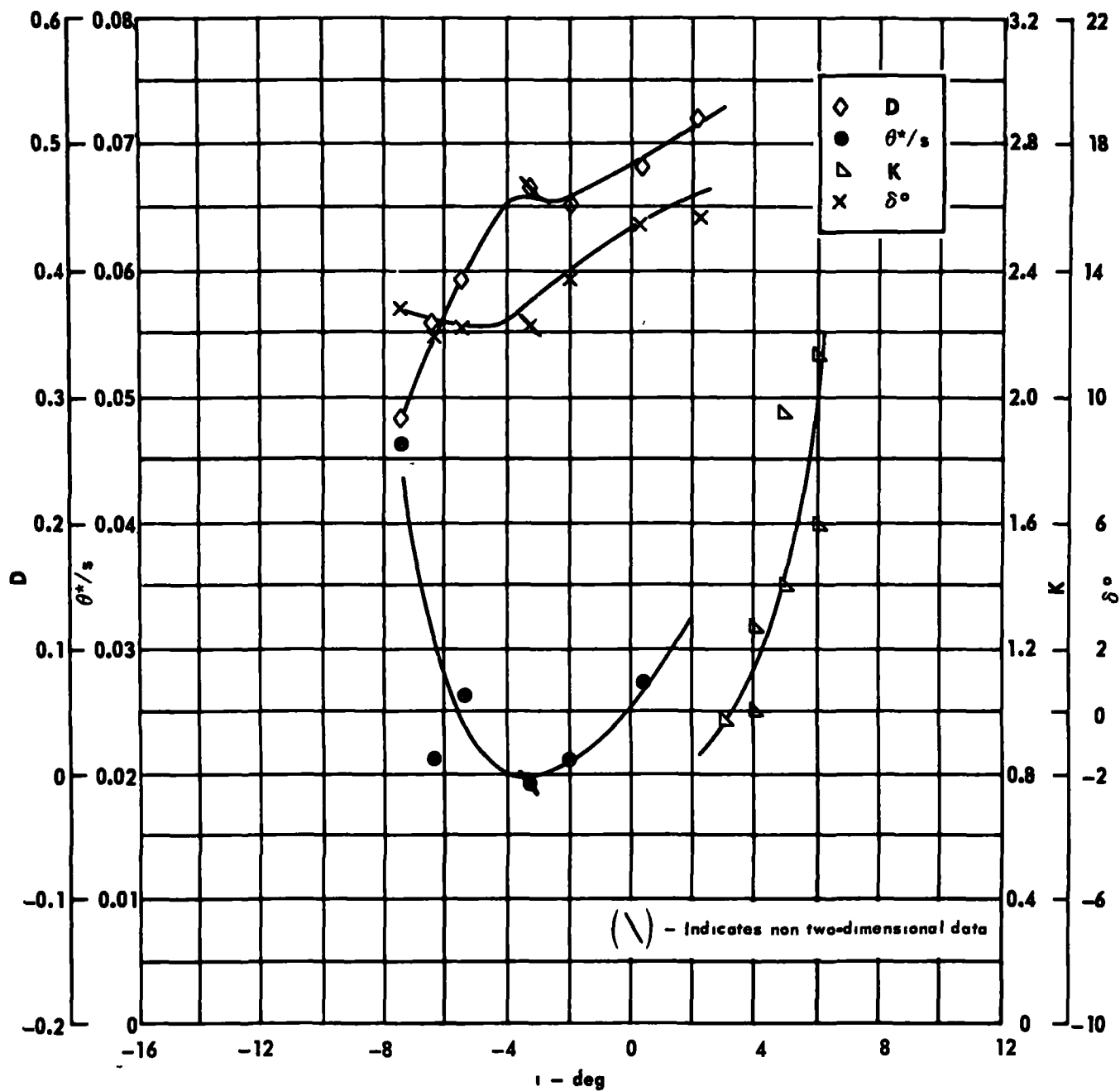


Cascade configuration $\beta_{1N} = 70$, $\sigma = 1.00$

M606 profile $\phi = 25$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 33. - Cascade characteristics as functions of incidence.

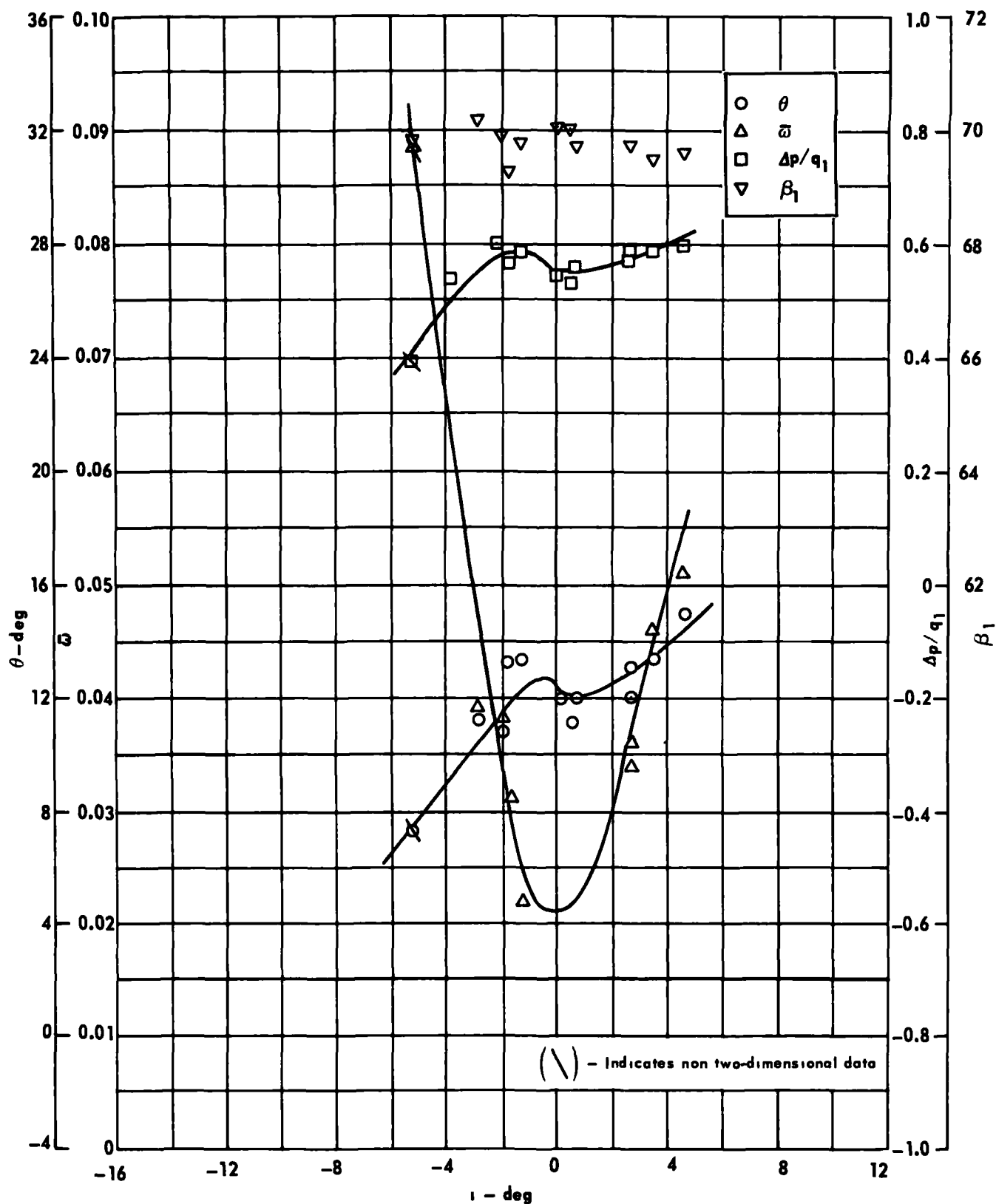


Cascade configuration $\beta_N = 70$, $\sigma = 1.00$

M606 profile: $\phi = 25$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 33. - Concluded.

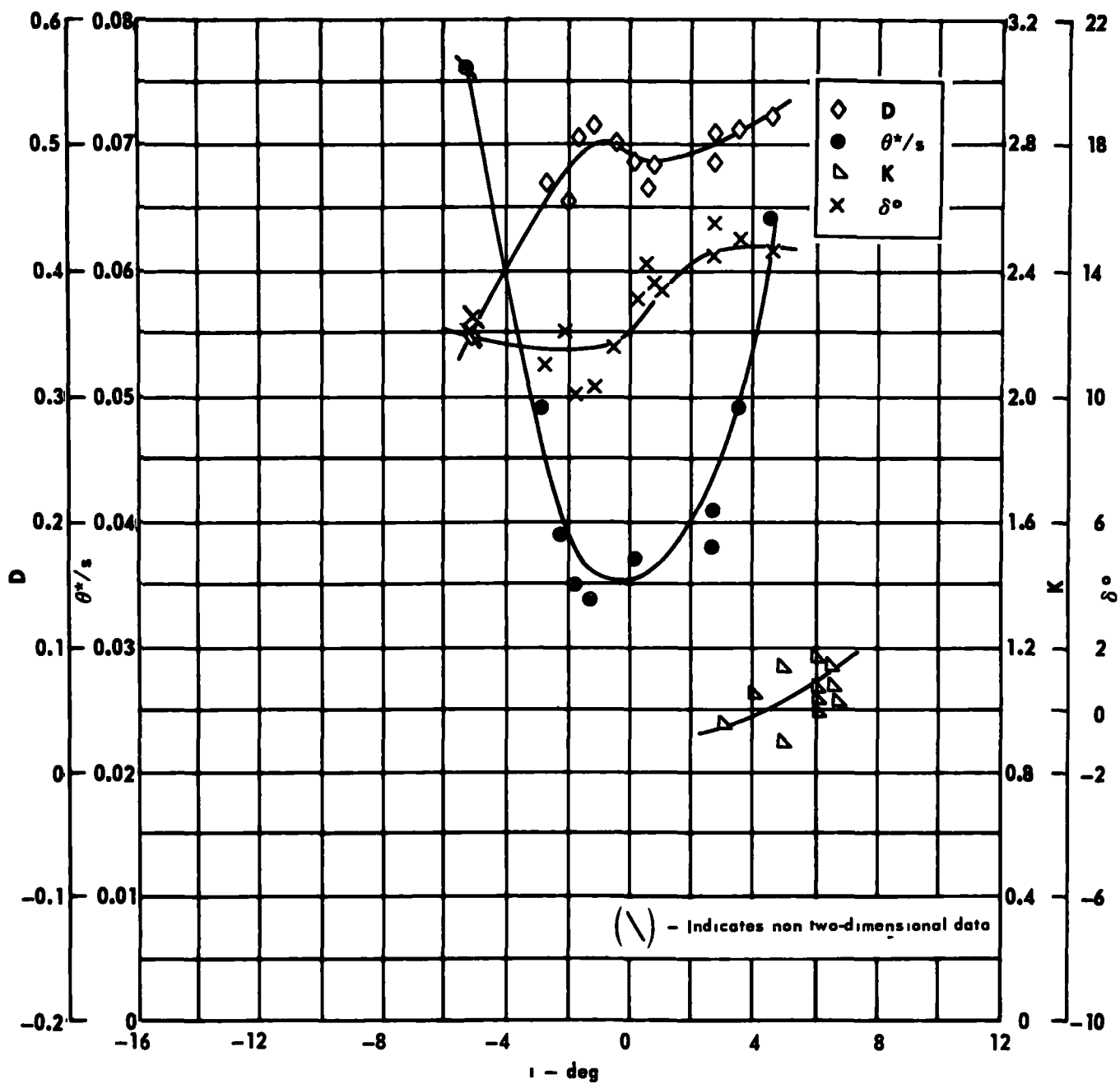


Cascade configuration $\beta_{1N} = 70$, $\sigma = 1.50$

M606 profile $\phi = 25$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 34. - Cascade characteristics as functions of incidence.

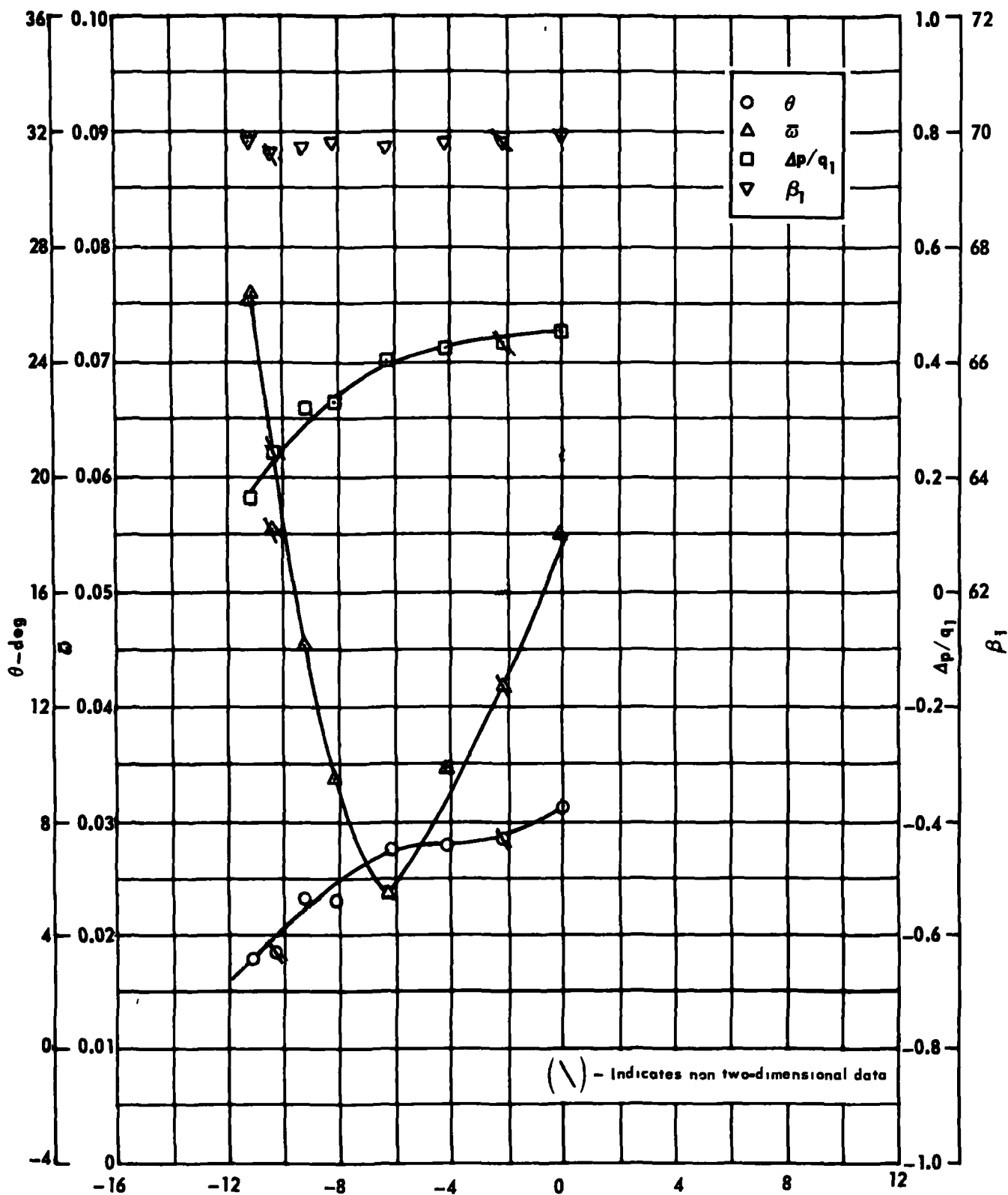


Cascade configuration $\beta_{1N} = 70$, $\sigma = 1.50$

M606 profile: $\phi = 25$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 34 . - Concluded.

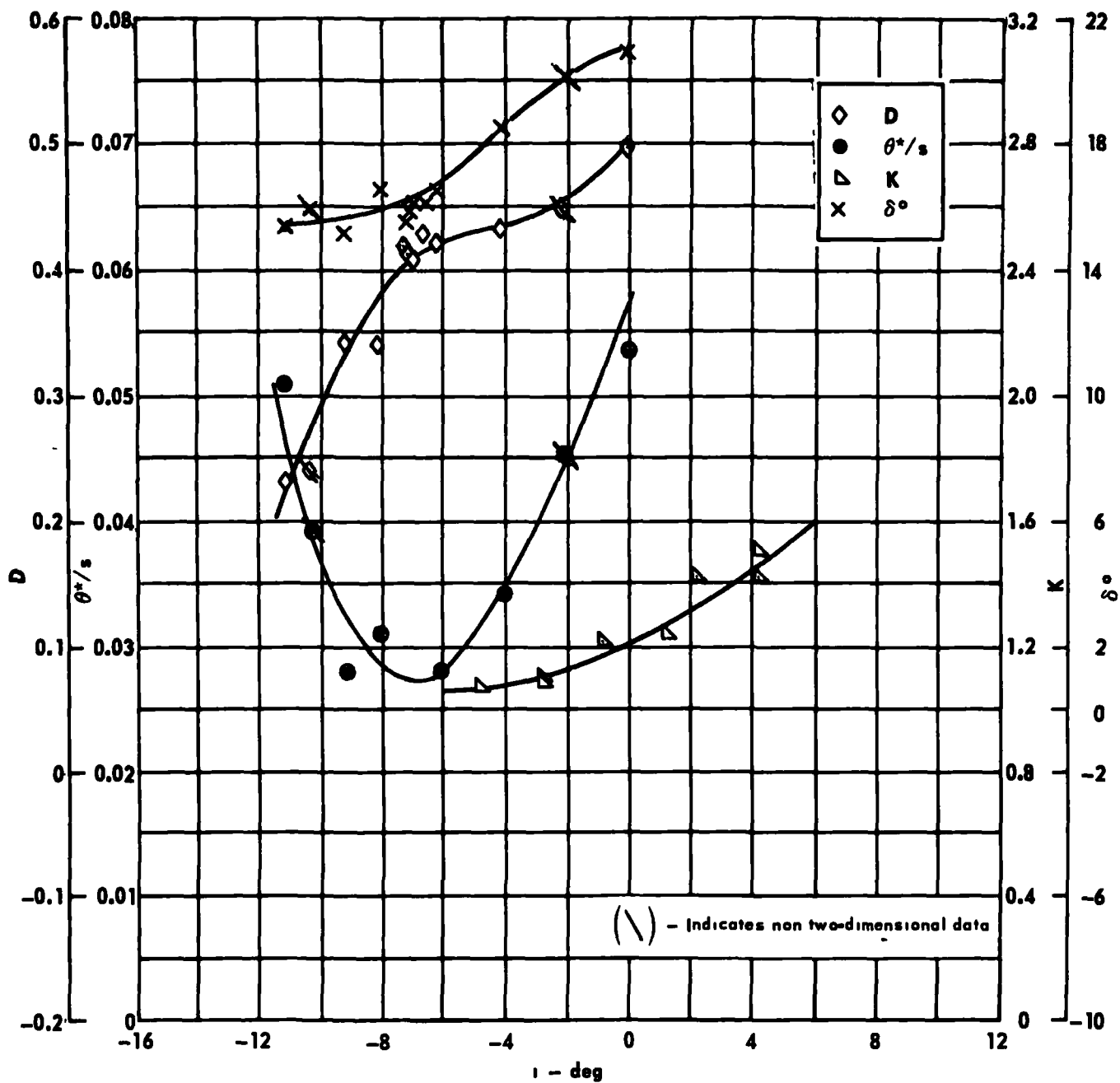


Cascade configuration $\beta_{1N} = 70, \sigma = 0.75$

M606 profile $\phi = 30, t/c = 0.06$

(a) $\theta, \omega, \Delta p/q_1, \beta_1$

Figure 35. - Cascade characteristics as functions of incidence.

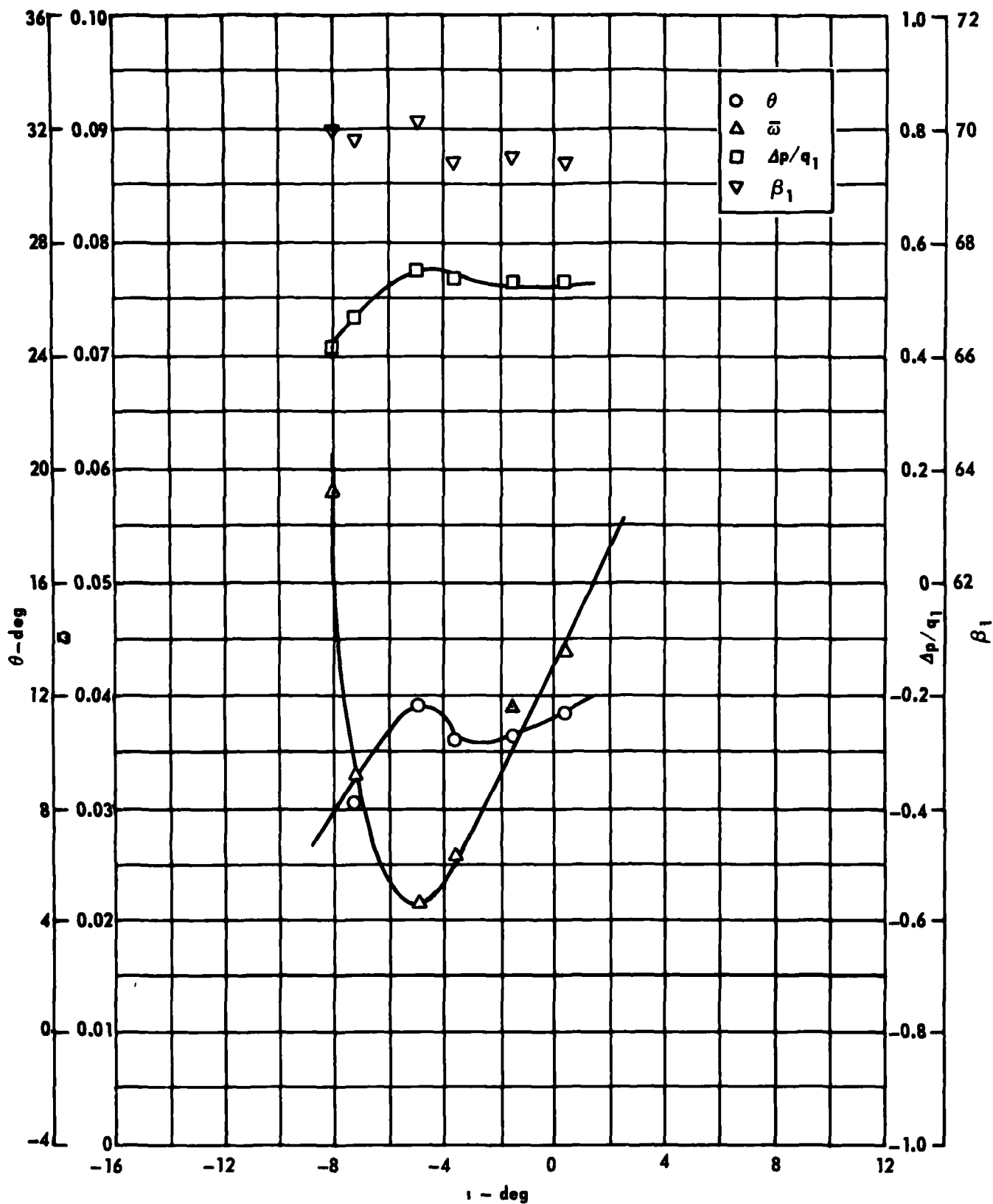


Cascade configuration $\beta_{1N} = 70$, $\sigma = 0.75$

M606 profile: $\phi = 30$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 35 . - Concluded.

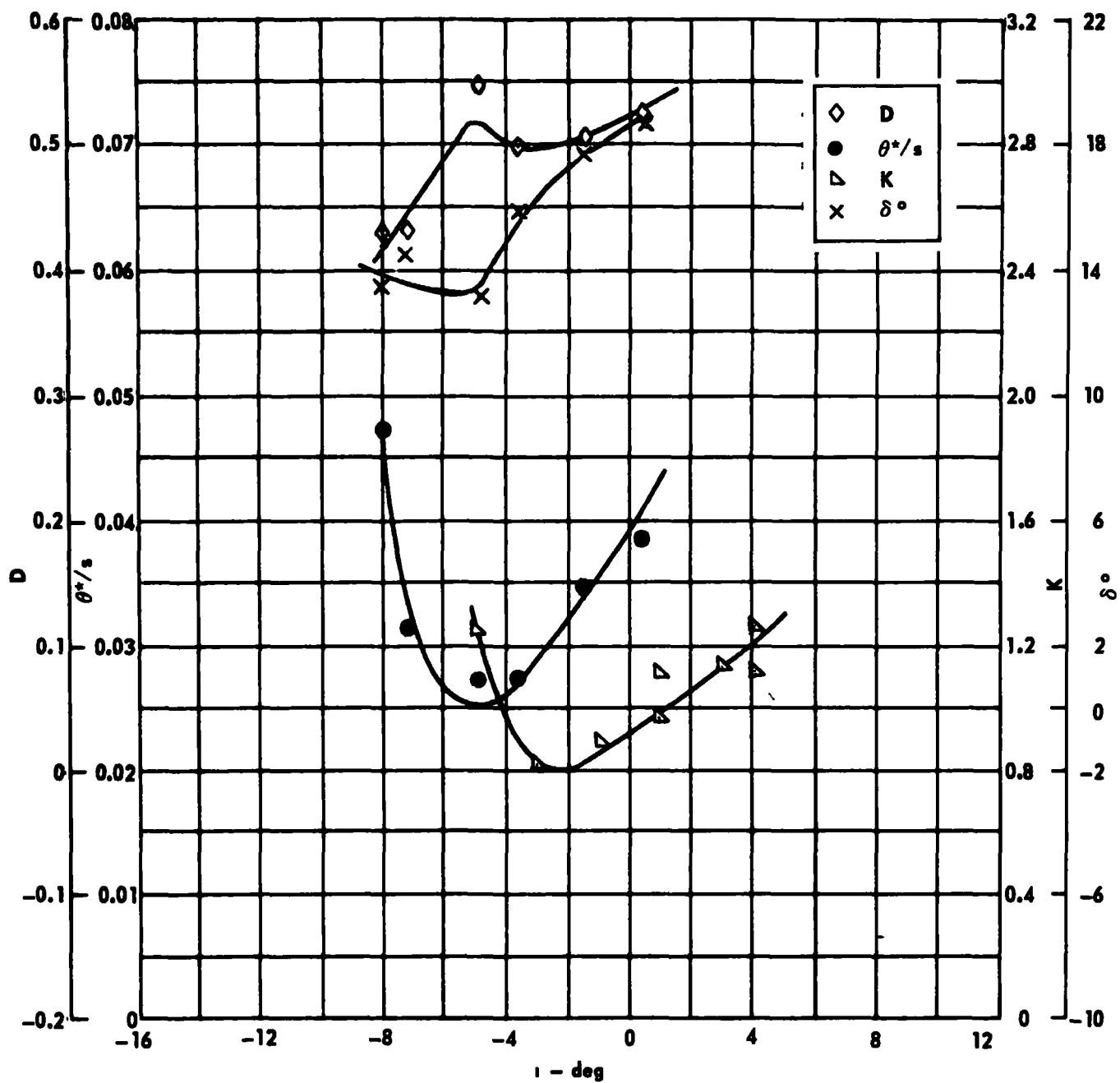


Cascade configuration $\beta_{1N} = 70, \sigma = 1.00$

M606 profile $\phi = 30, t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 36. - Cascade characteristics as functions of incidence.



Cascade configuration $\beta_{1N} = 70$, $\sigma = 1.00$

M606 profile $\phi = 30$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 36. - Concluded.

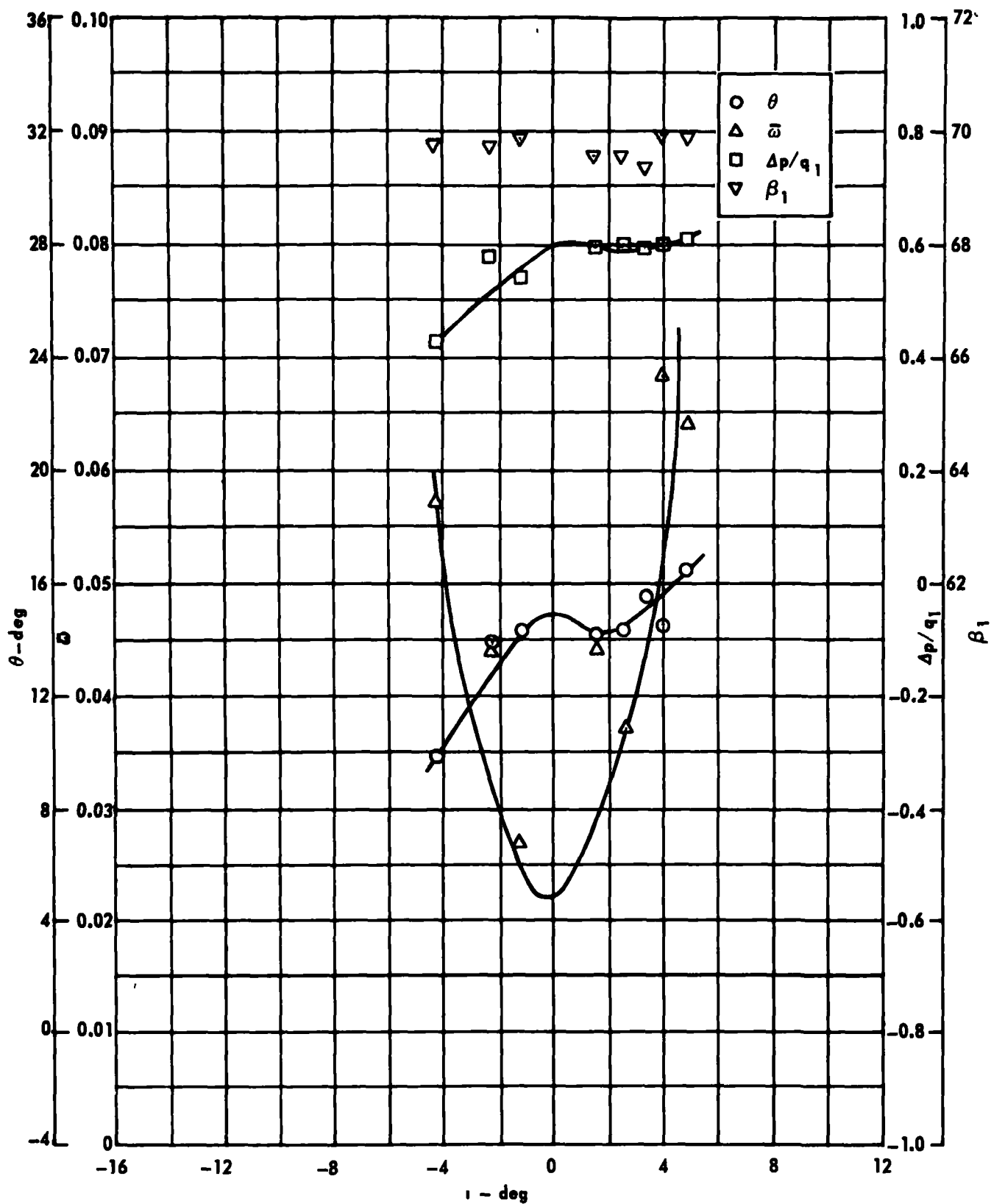
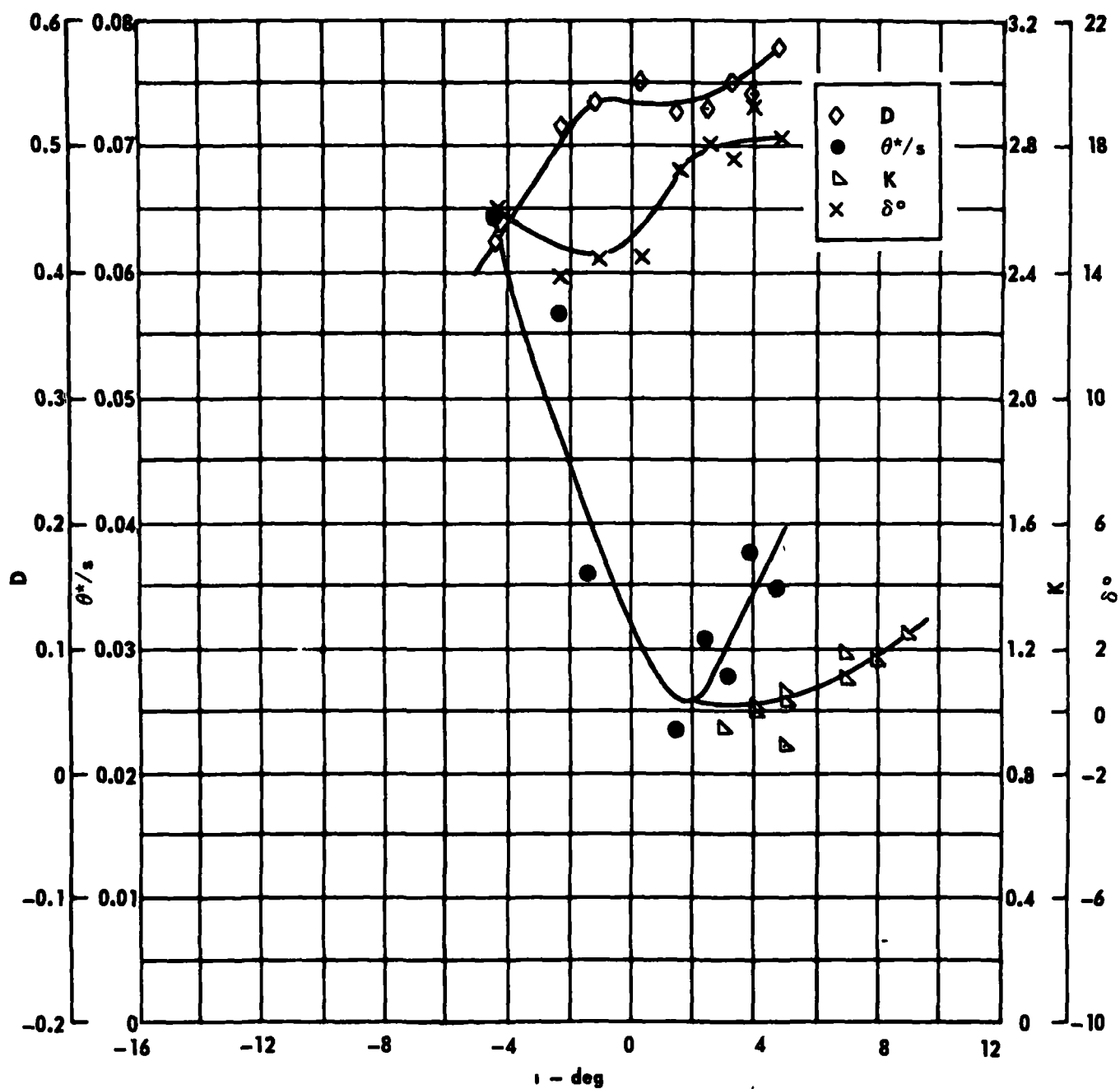


Figure 37. - Cascade characteristics as functions of incidence.

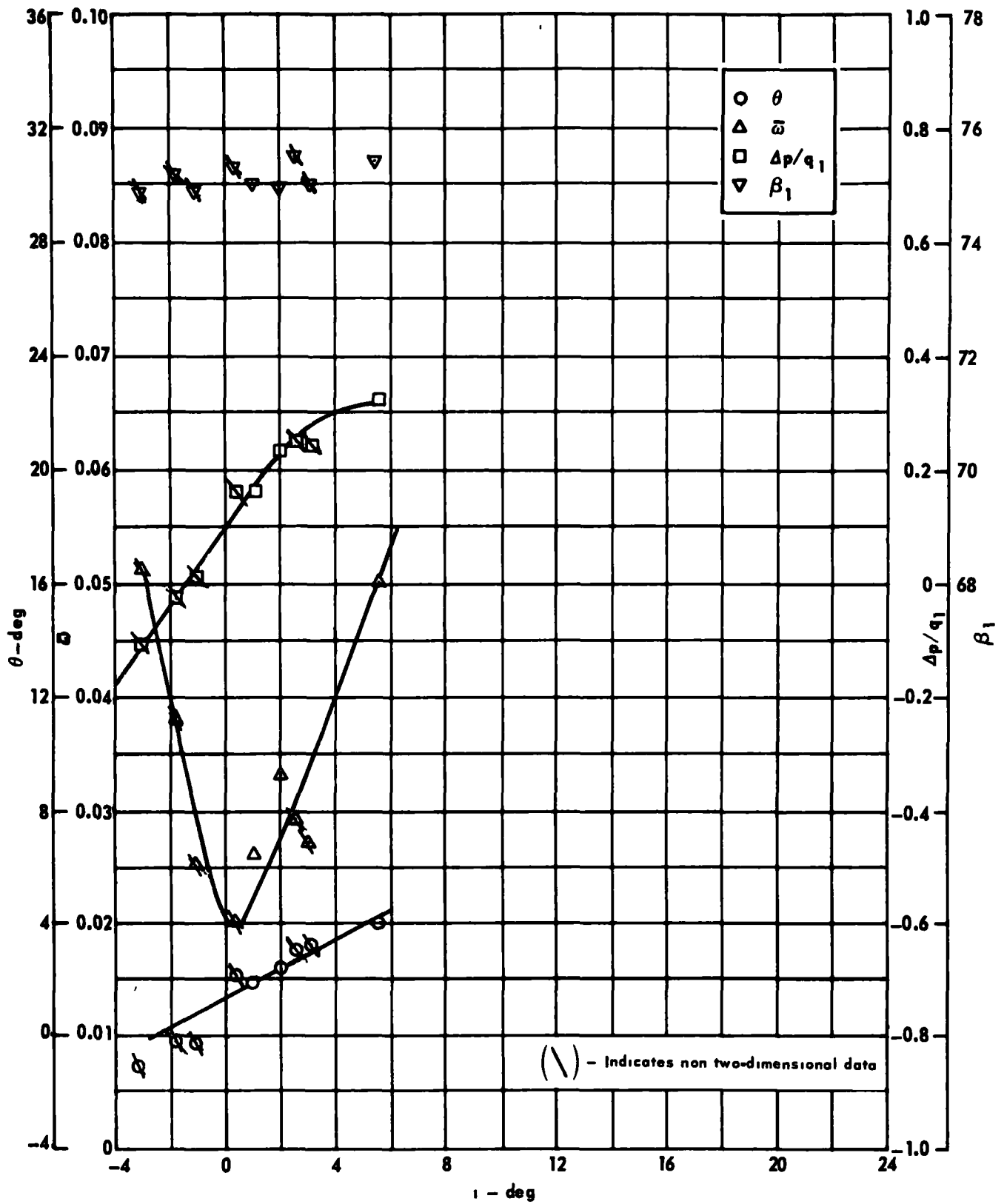


Cascade configuration $\beta_{1N} = 70$, $\sigma = 1.50$

M606 profile $\phi = 30$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 37. - Concluded.

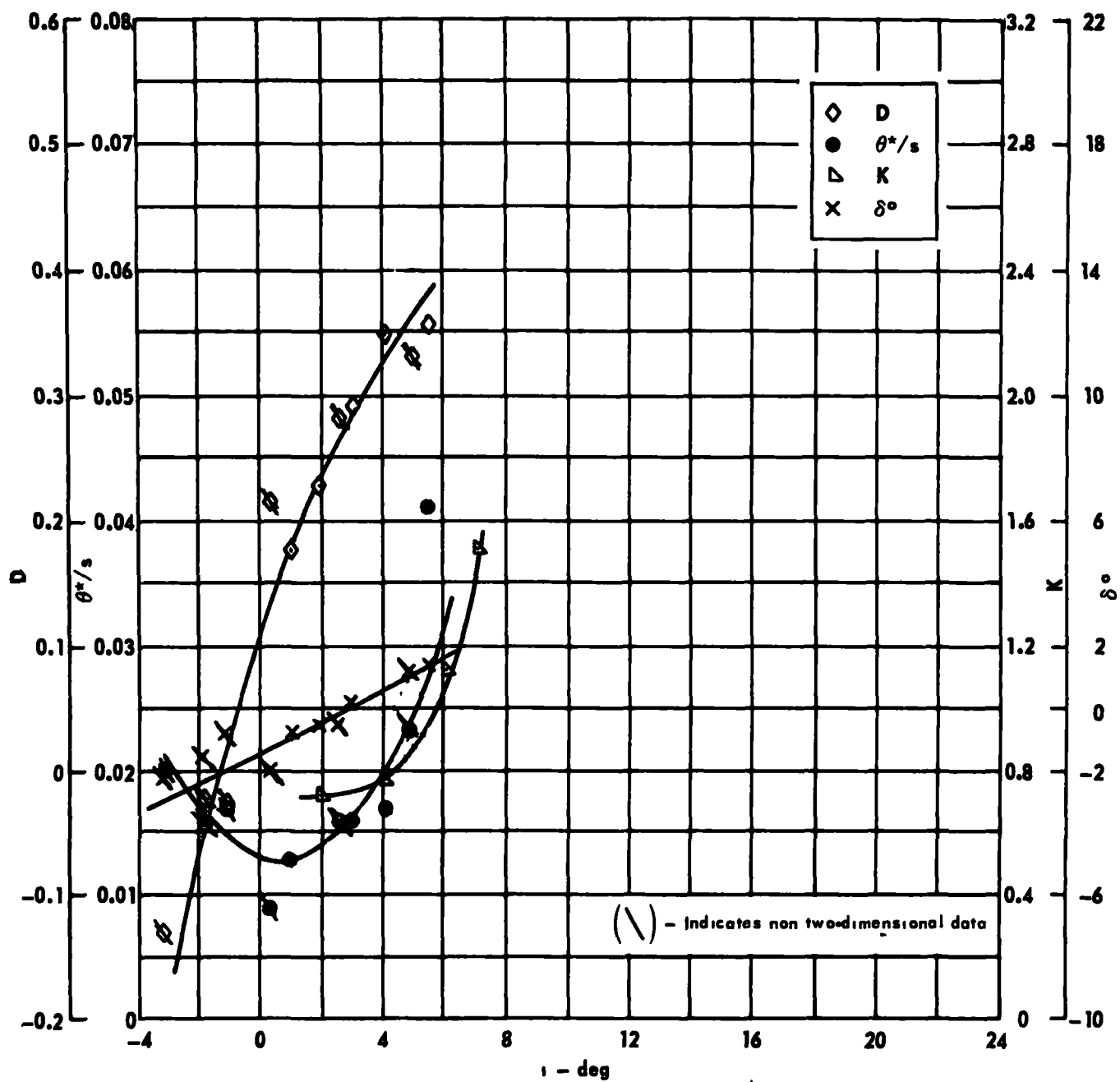


Cascade configuration $\beta_{1N} = 75$, $\sigma = 0.75$

M606 profile $\phi = 0$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 38. - Cascade characteristics as functions of incidence.



Cascade configuration $\beta_{1N} = 75$, $\sigma = 0.75$

M606 profile $\phi = 0$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 38. - Concluded.

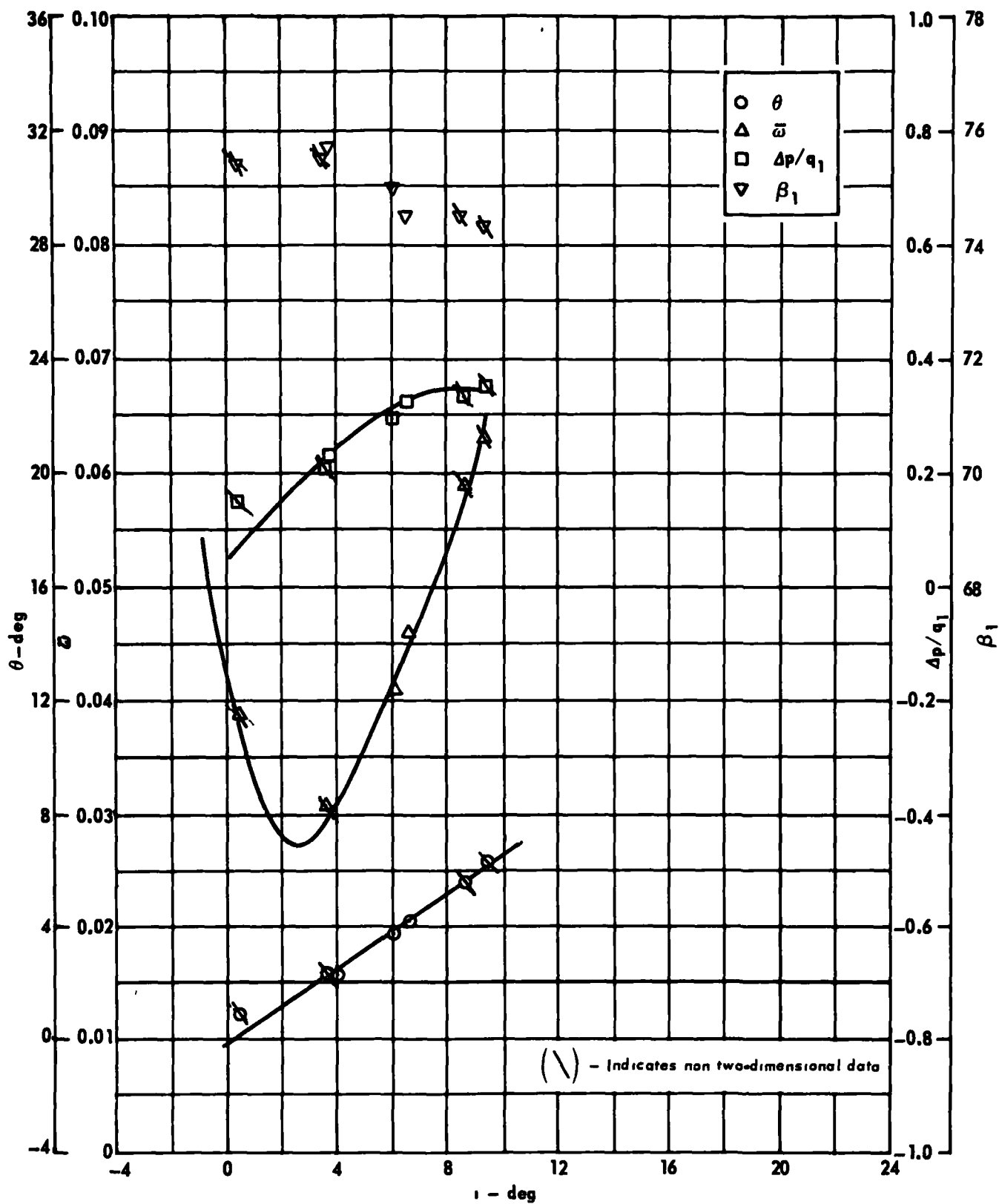
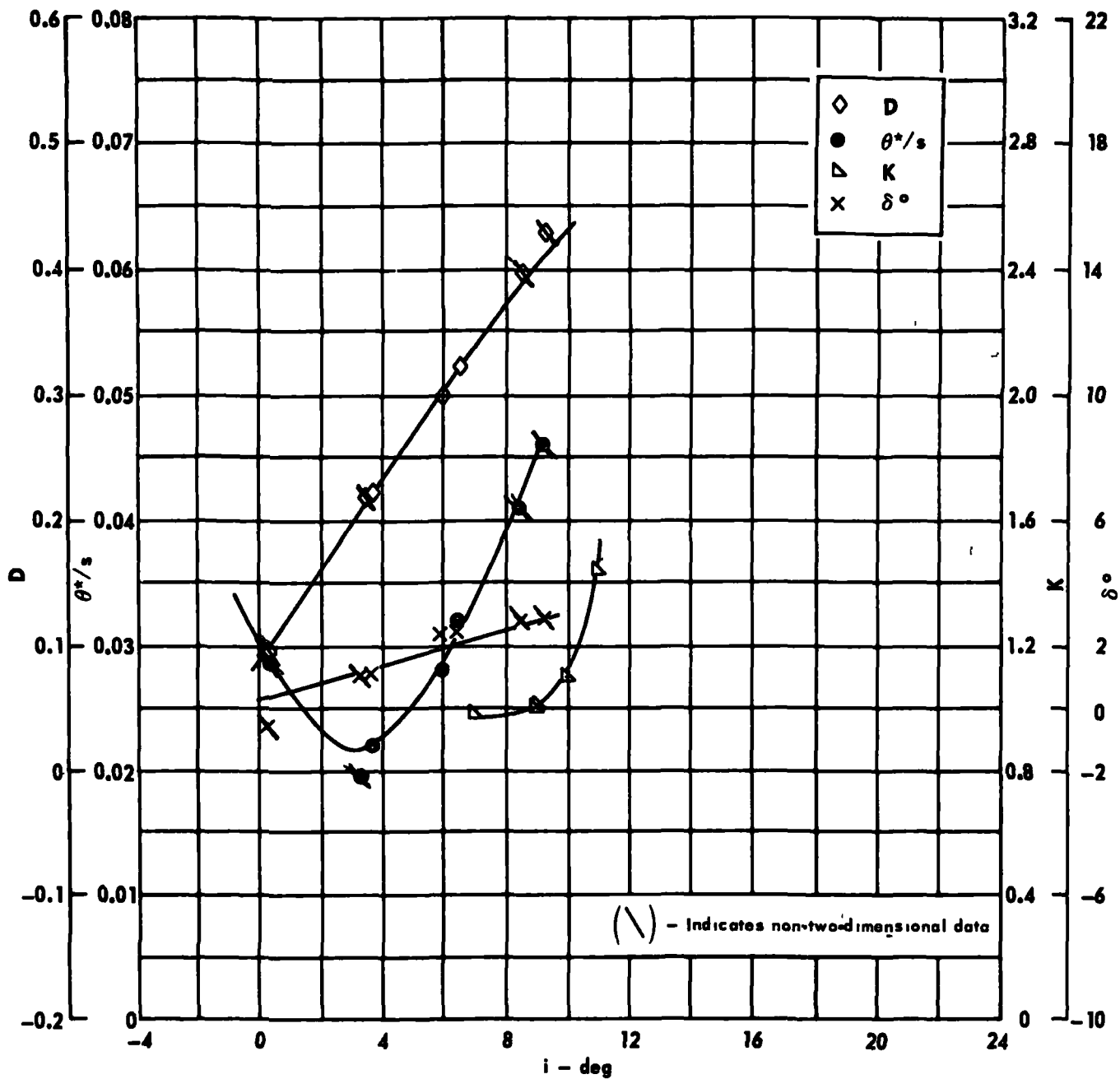


Figure 39. - Cascade characteristics as functions of incidence.

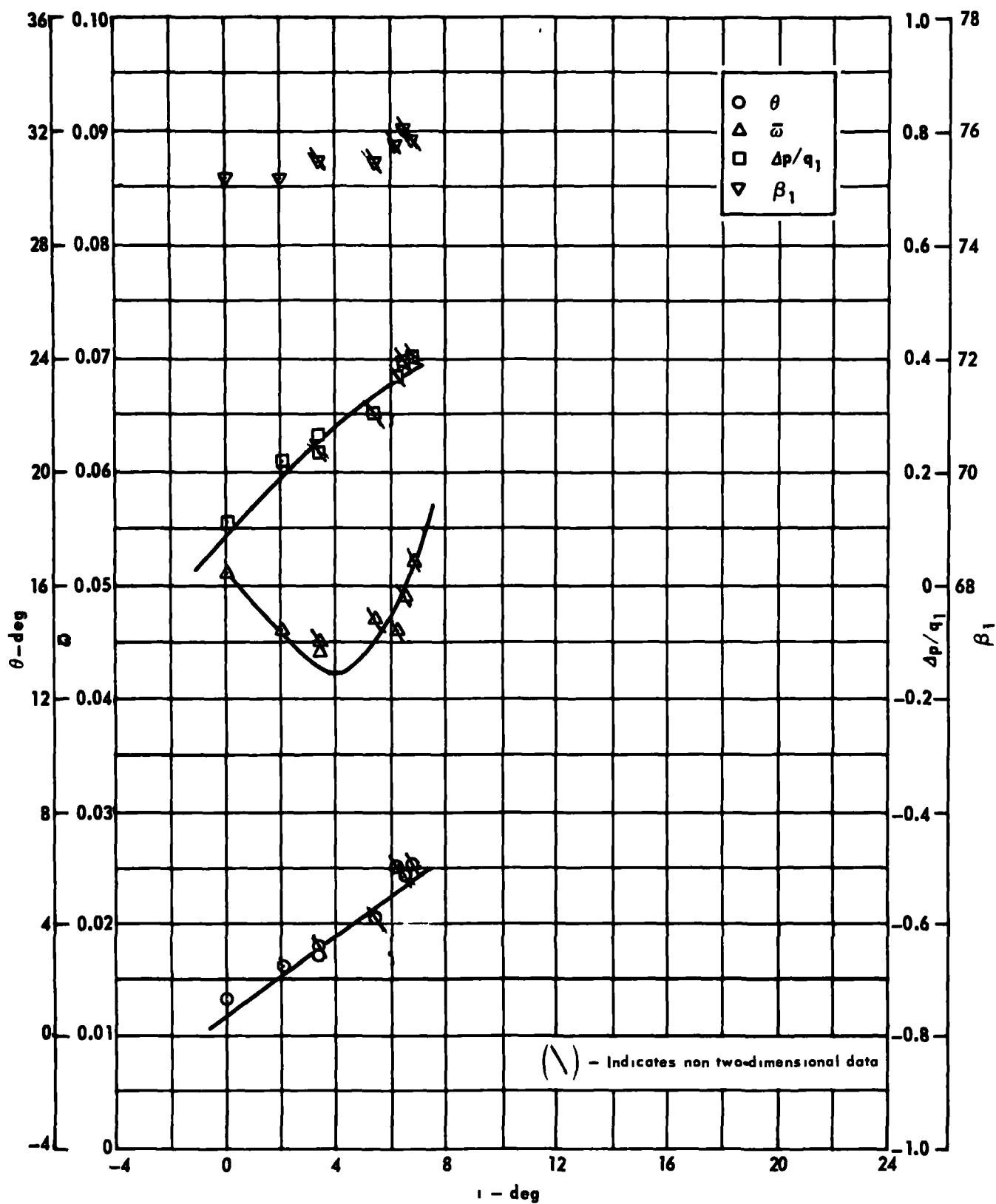


Cascade configuration $\beta_{1N} = 75$, $\sigma = 1.00$

M606 profile $\phi = 0$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 39. - Concluded.

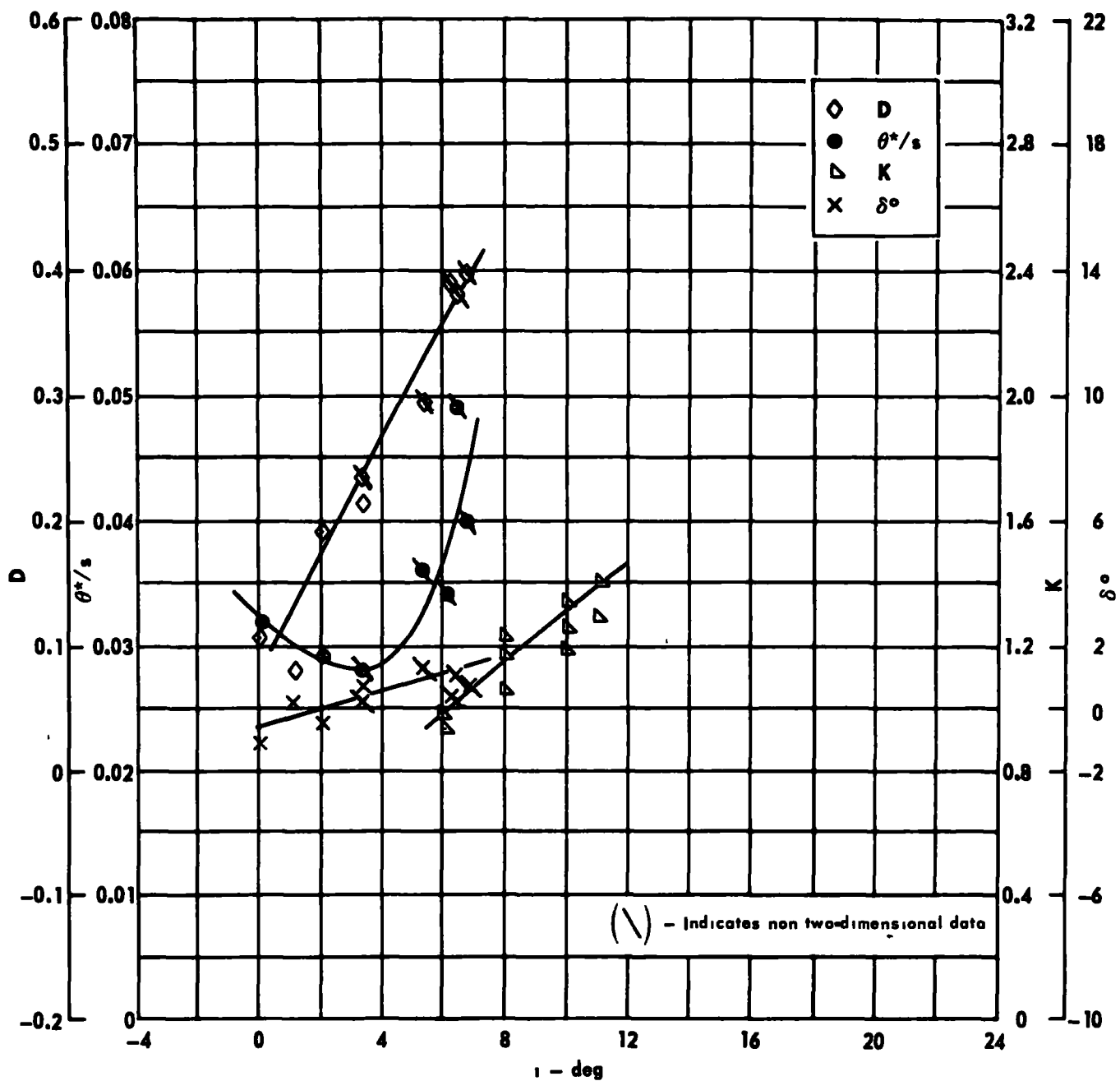


Cascade configuration $\beta_{1N} = 75$, $\sigma = 1.50$

M606 profile $\phi = 0$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 40. - Cascade characteristics as functions of incidence.

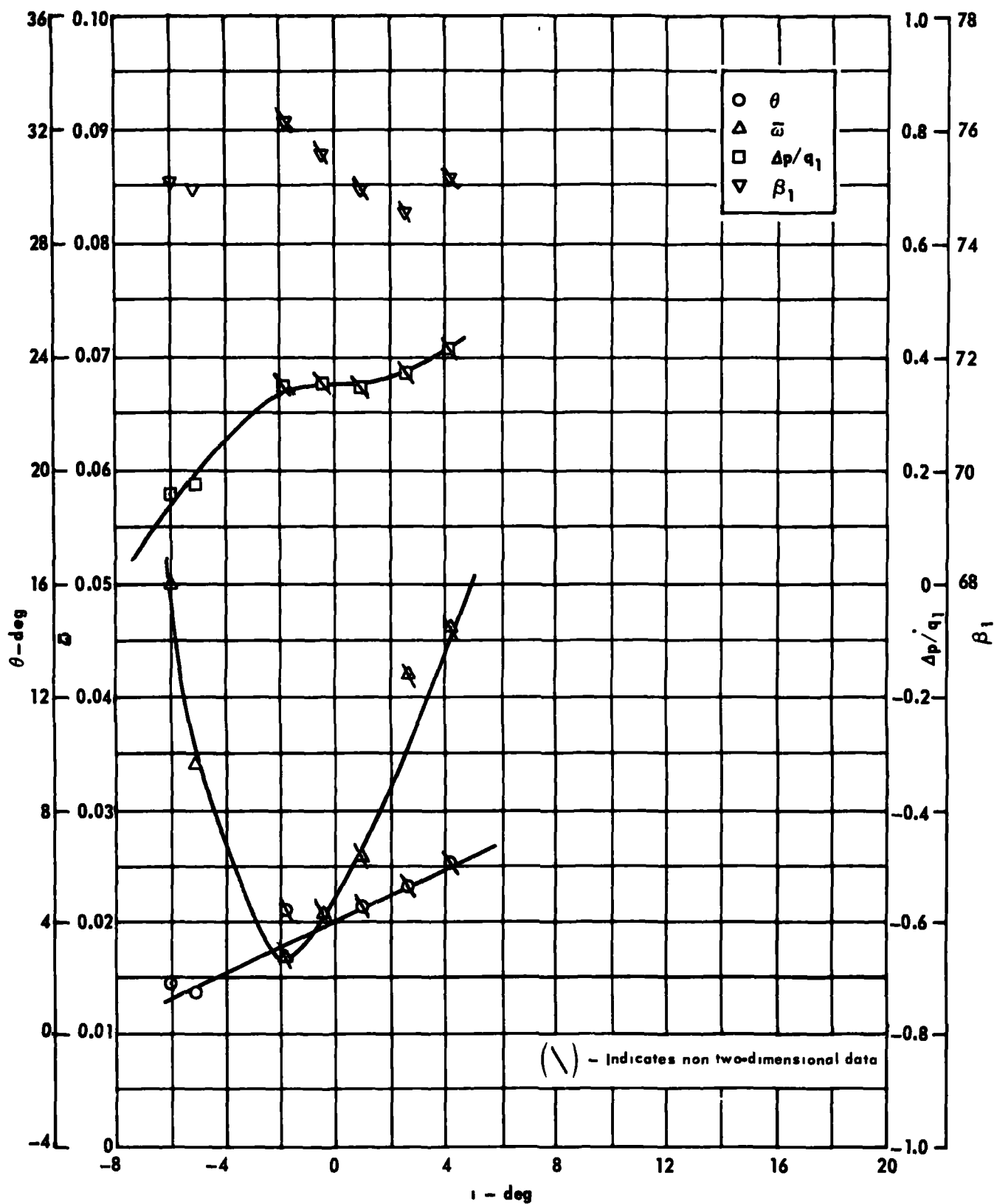


Cascade configuration $\beta_N = 75^\circ$, $\sigma = 1.50$

M606 profile: $\phi = 0$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 40 . - Concluded.

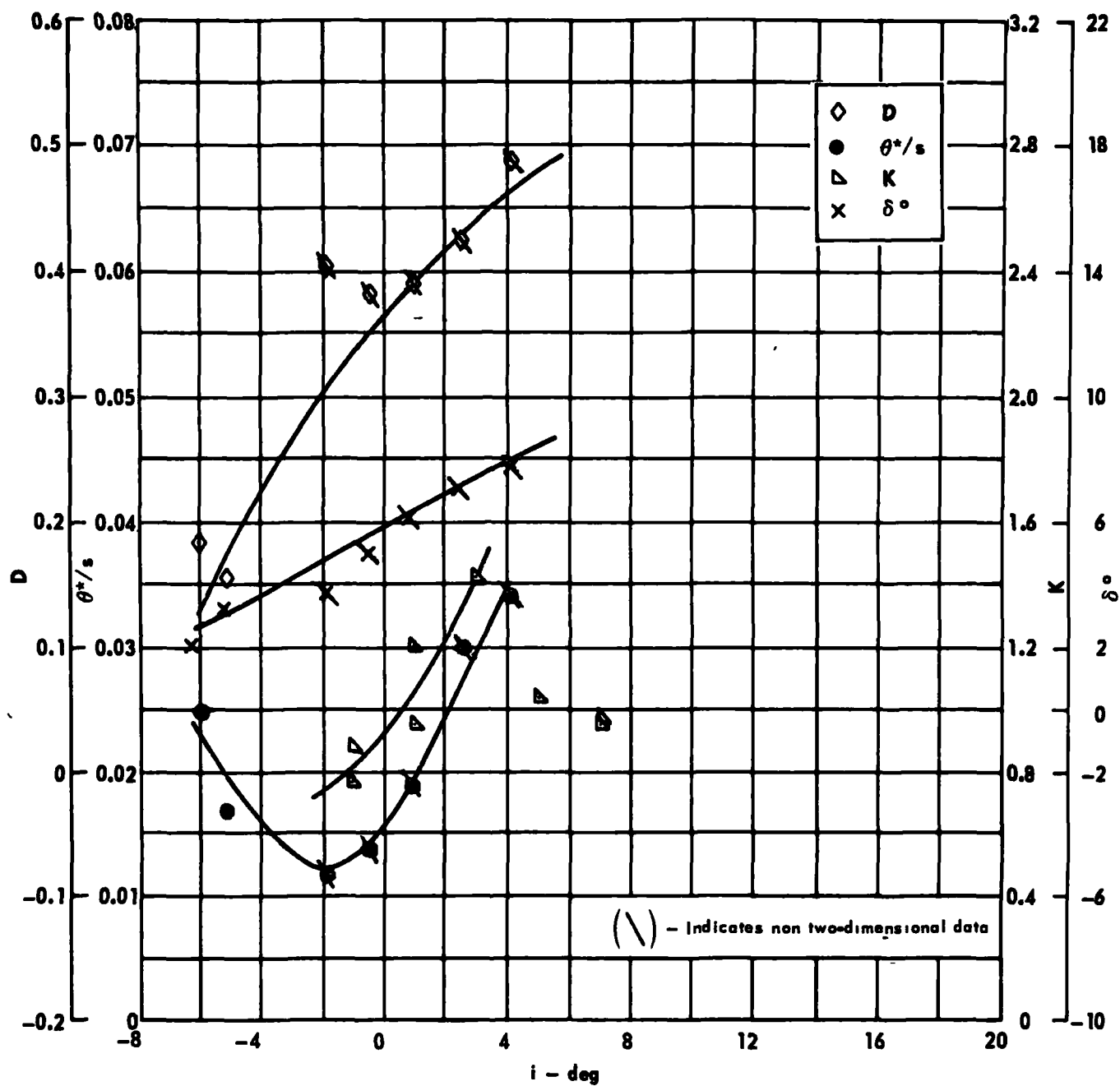


Cascade configuration $\beta_{1N} = 75$, $\sigma = 0.75$

M606 profile $\phi = 10$, $t/c = 0.06$

(a) $\theta, \omega, \Delta p/q_1, \beta_1$

Figure 41. - Cascade characteristics as functions of incidence.



Cascade configuration $\beta_{1N} = 75, \sigma = 0.75$

M606 profile $\phi = 10, t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 41. - Concluded.

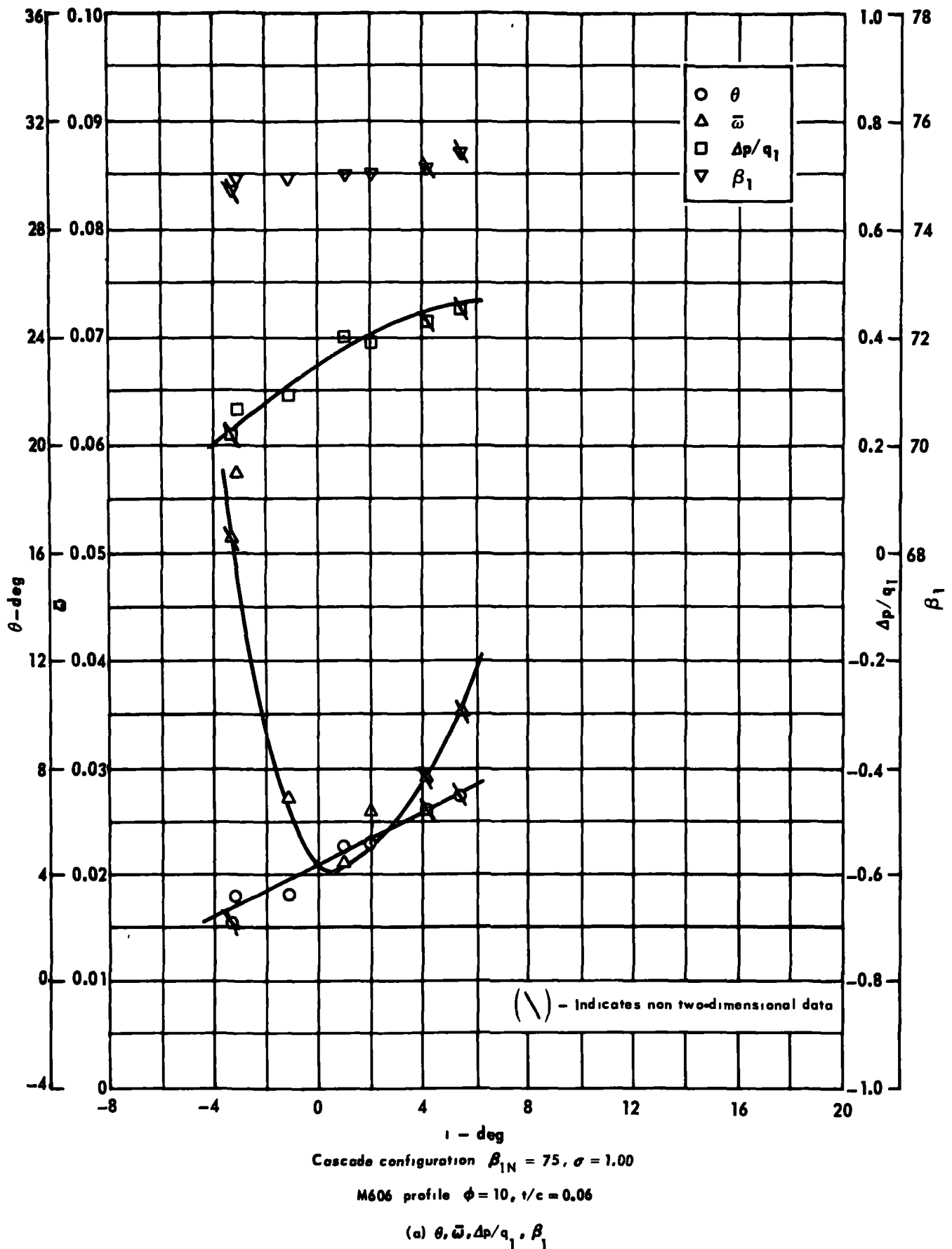
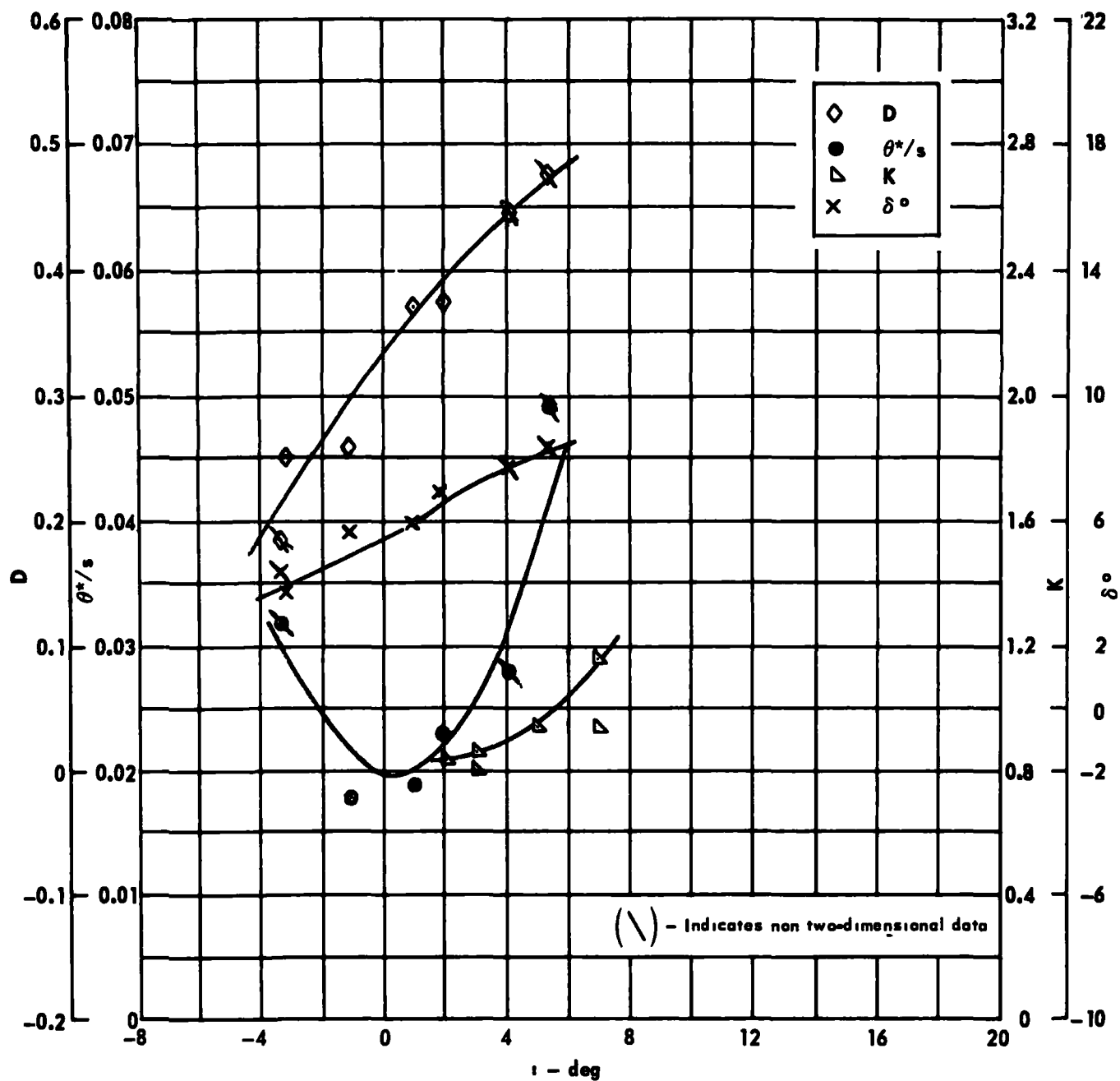


Figure 42. - Cascade characteristics as functions of incidence.

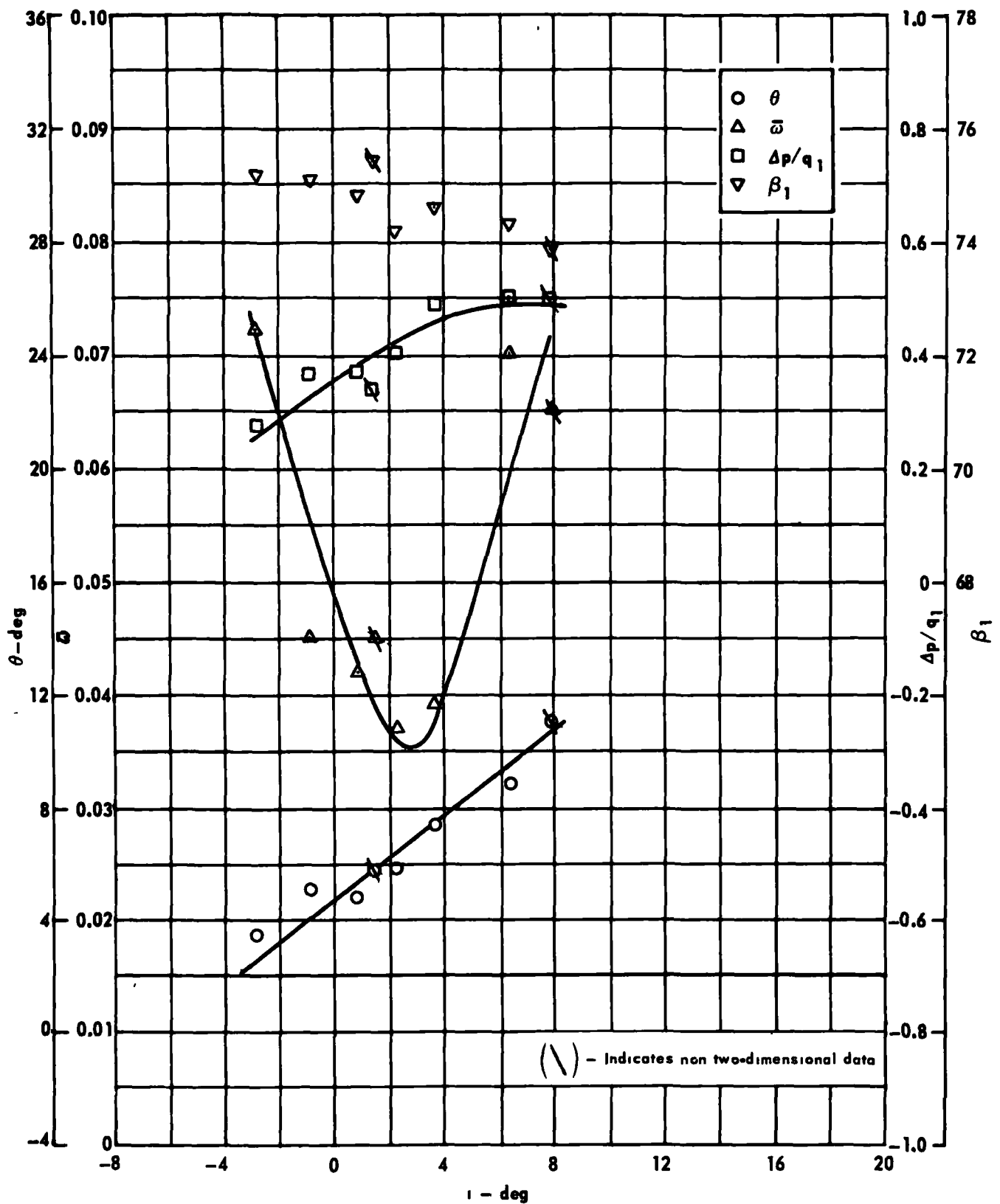


Cascade configuration $\beta_{1N} = 75$, $\sigma = 1.00$

M606 profile : $\phi = 10$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 42. - Concluded.

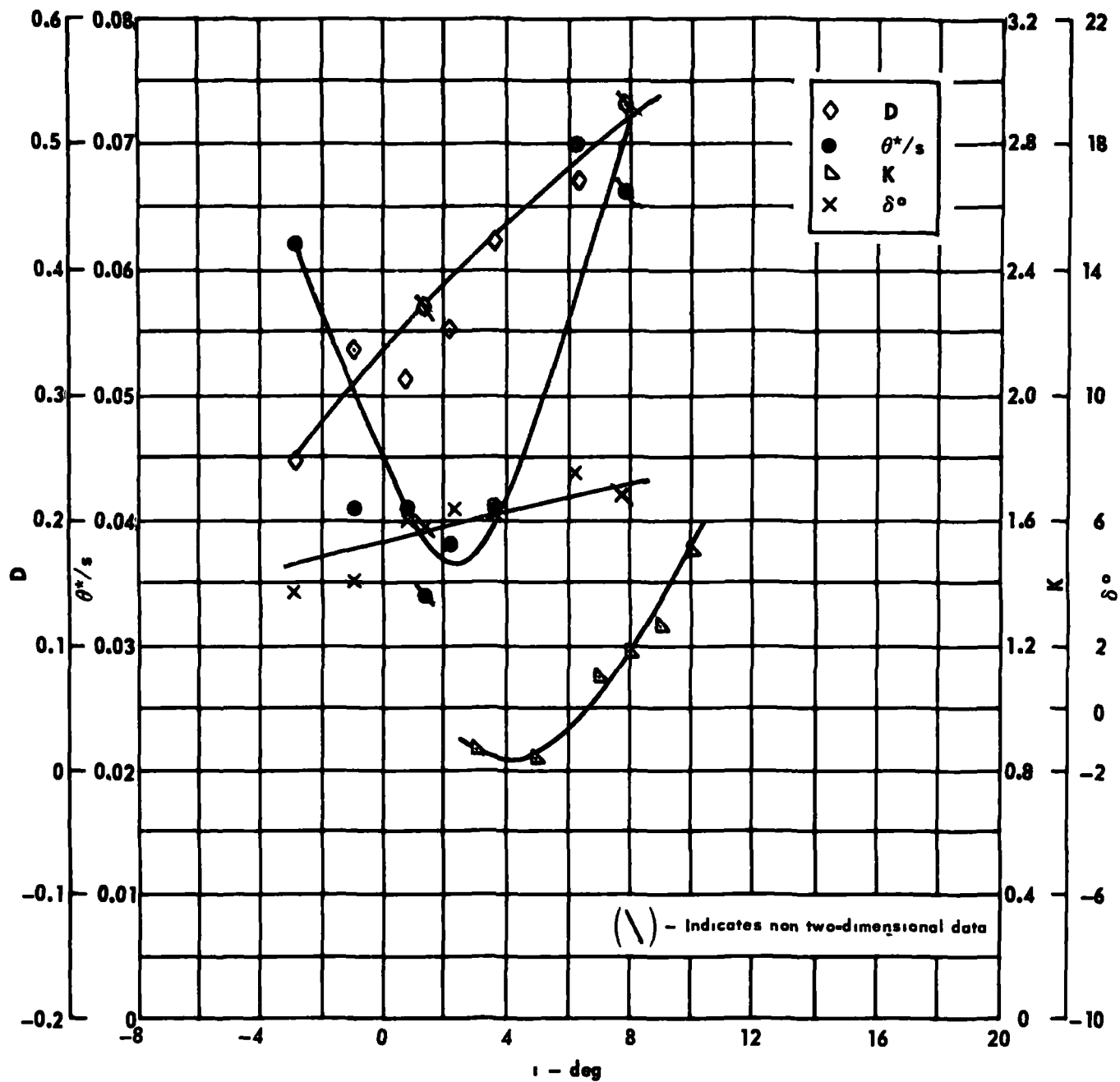


Cascade configuration $\beta_{1N} = 75$, $\sigma = 1.50$

M606 profile $\phi = 10$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 43. - Cascade characteristics as functions of incidence.

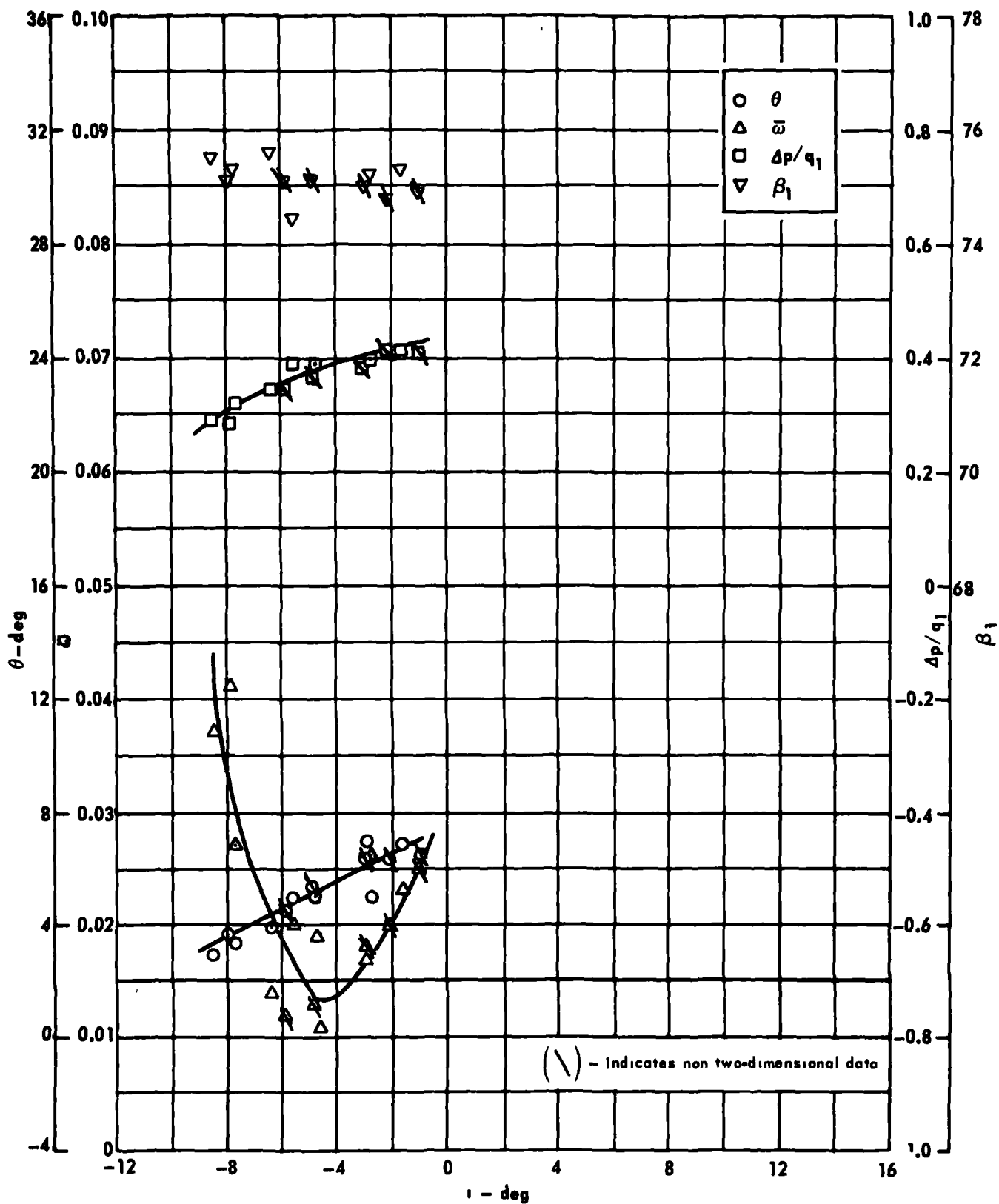


Cascade configuration $\beta_{1N} = 75$, $\sigma = 1.50$

M606 profile $\phi = 10$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 43. - Concluded.

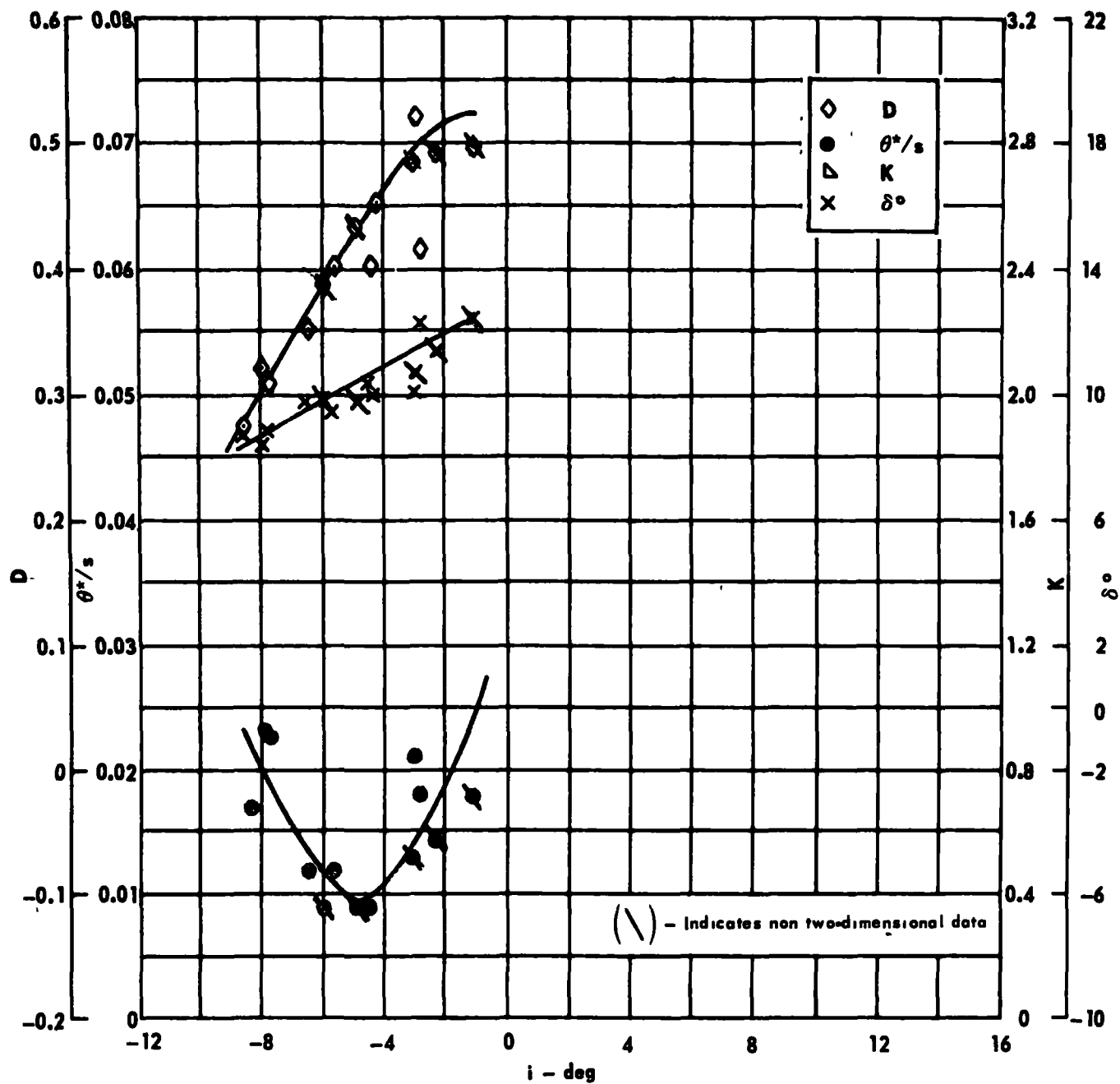


Cascade configuration $\beta_{1N} = 75, \sigma = 0.75$

M606 profile $\phi = 20, t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 44. - Cascade characteristics as functions of incidence.



Cascade configuration $\beta_{1N} = 75$, $\sigma = 0.75$

M606 profile $\phi = 20$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 44. - Concluded.

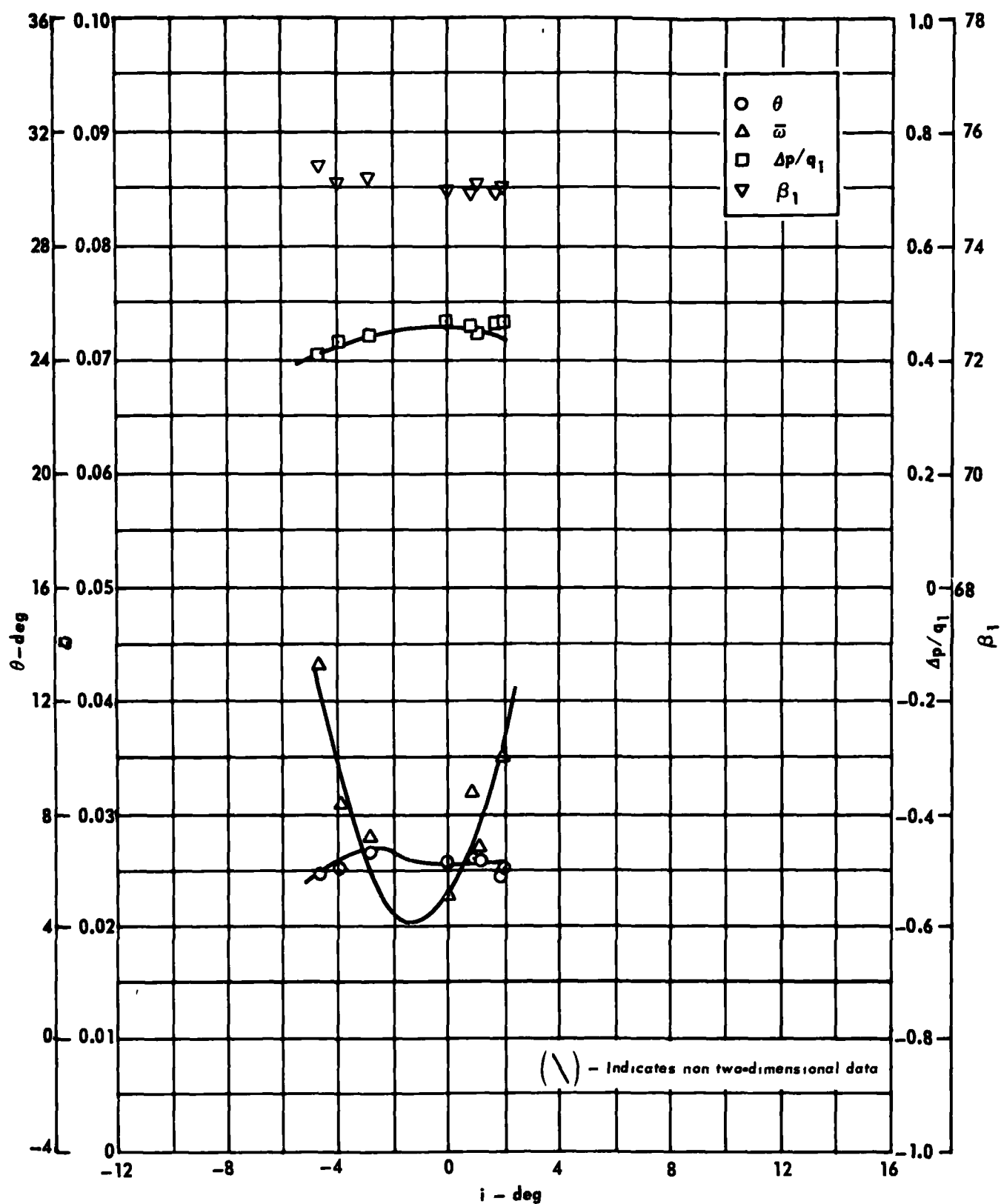
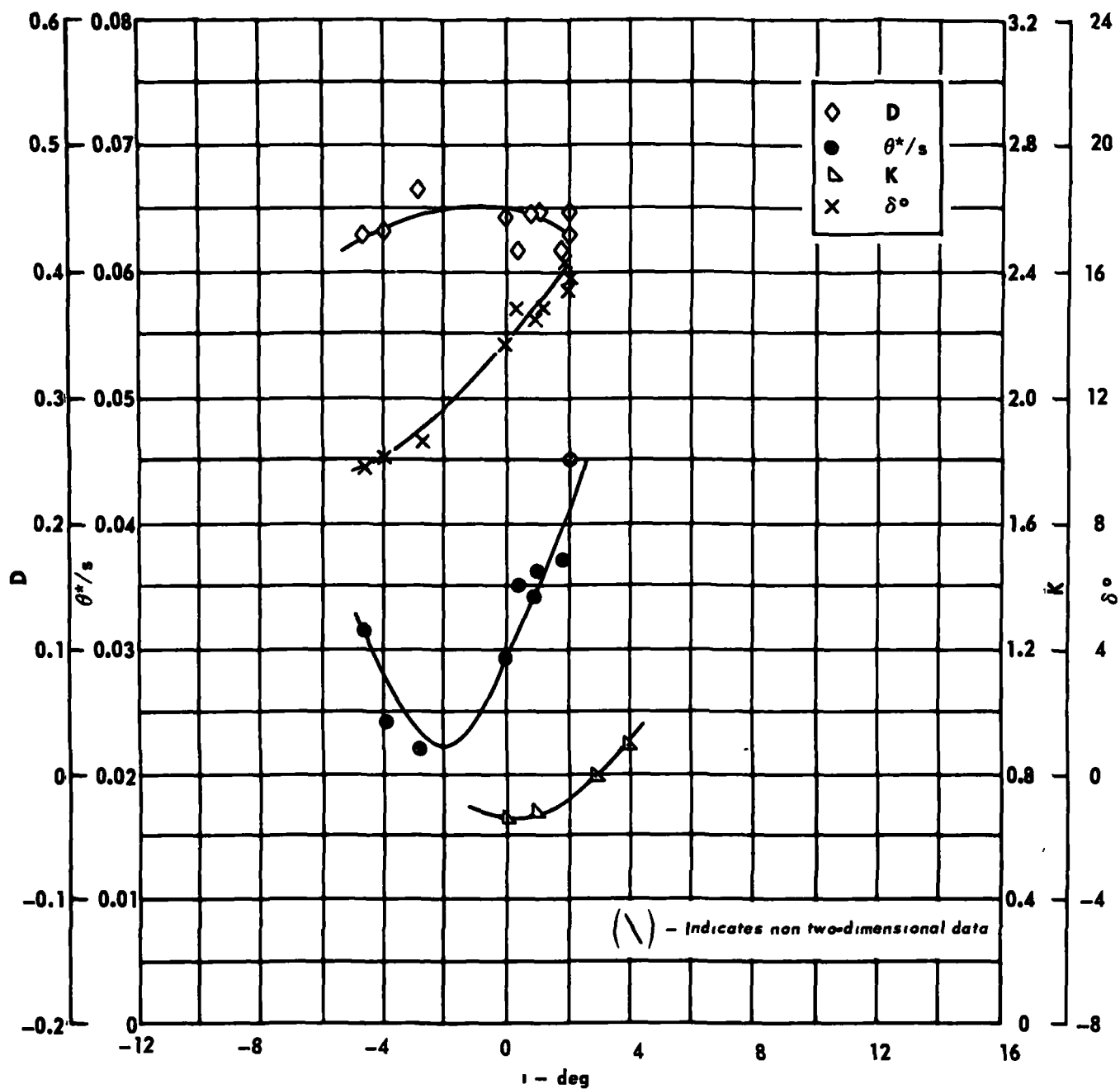


Figure 45. - Cascade characteristics as functions of incidence.

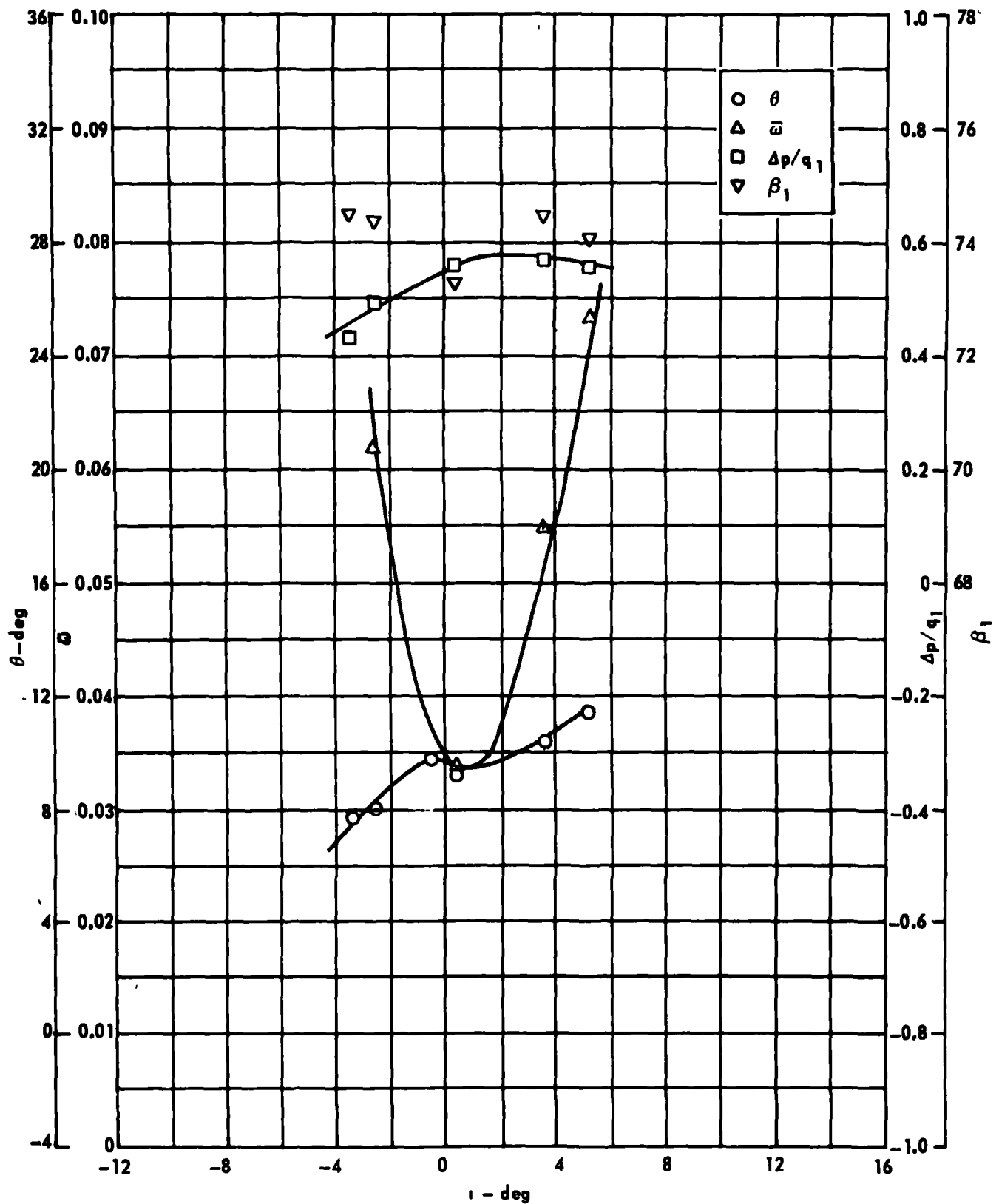


Cascade configuration $\beta_{1N} = 75$, $\sigma = 1.00$

M606 profile $\phi = 20$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 45. - Concluded.

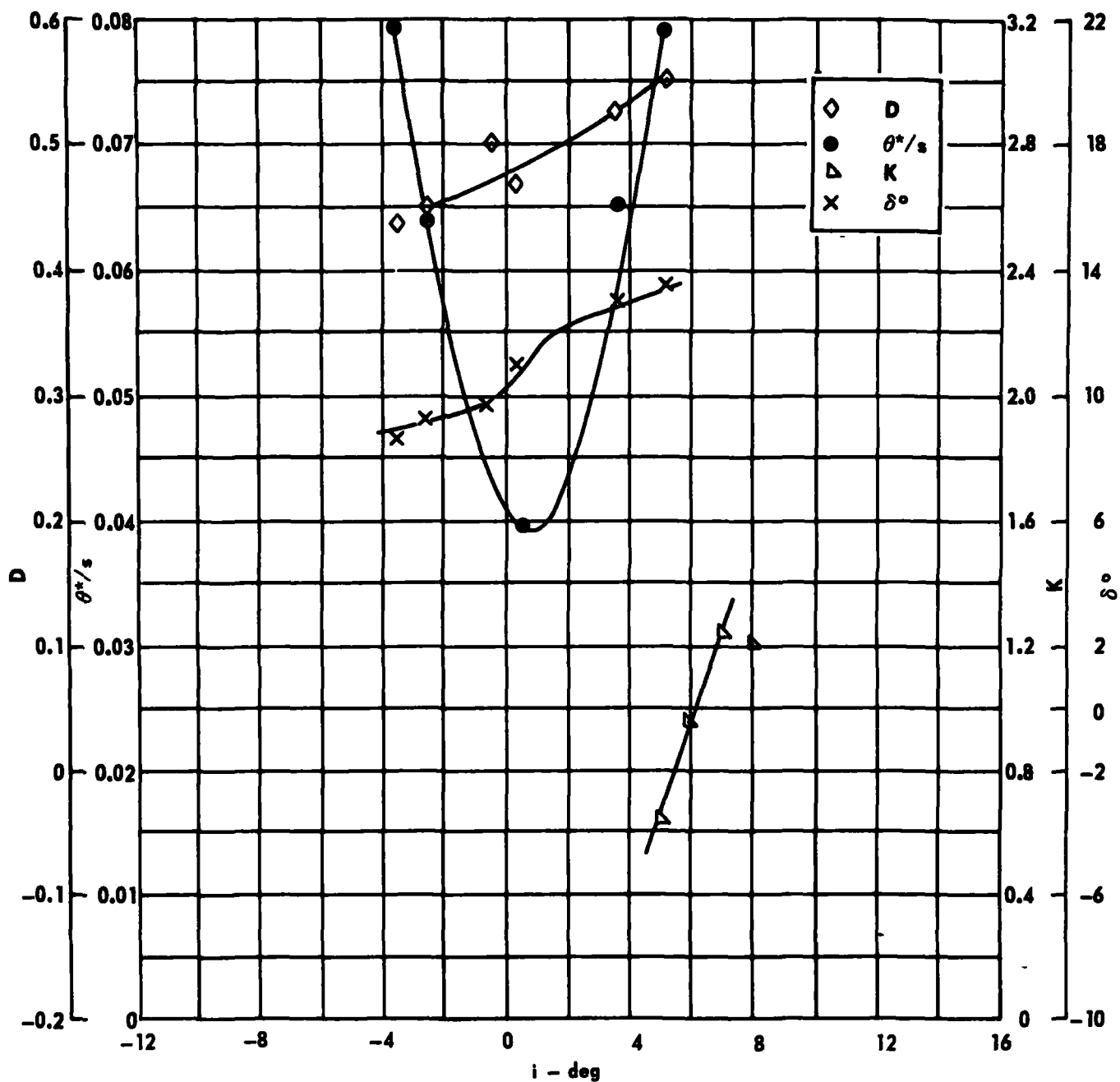


Cascade configuration $\beta_{1N} = 75$, $\sigma = 1.50$

M606 profile $\phi = 20$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 46. - Cascade characteristics as functions of incidence.



Cascade configuration $\beta_N = 75, \sigma = 1.50$

M606 profile $\phi = 20, t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 46. - Concluded.

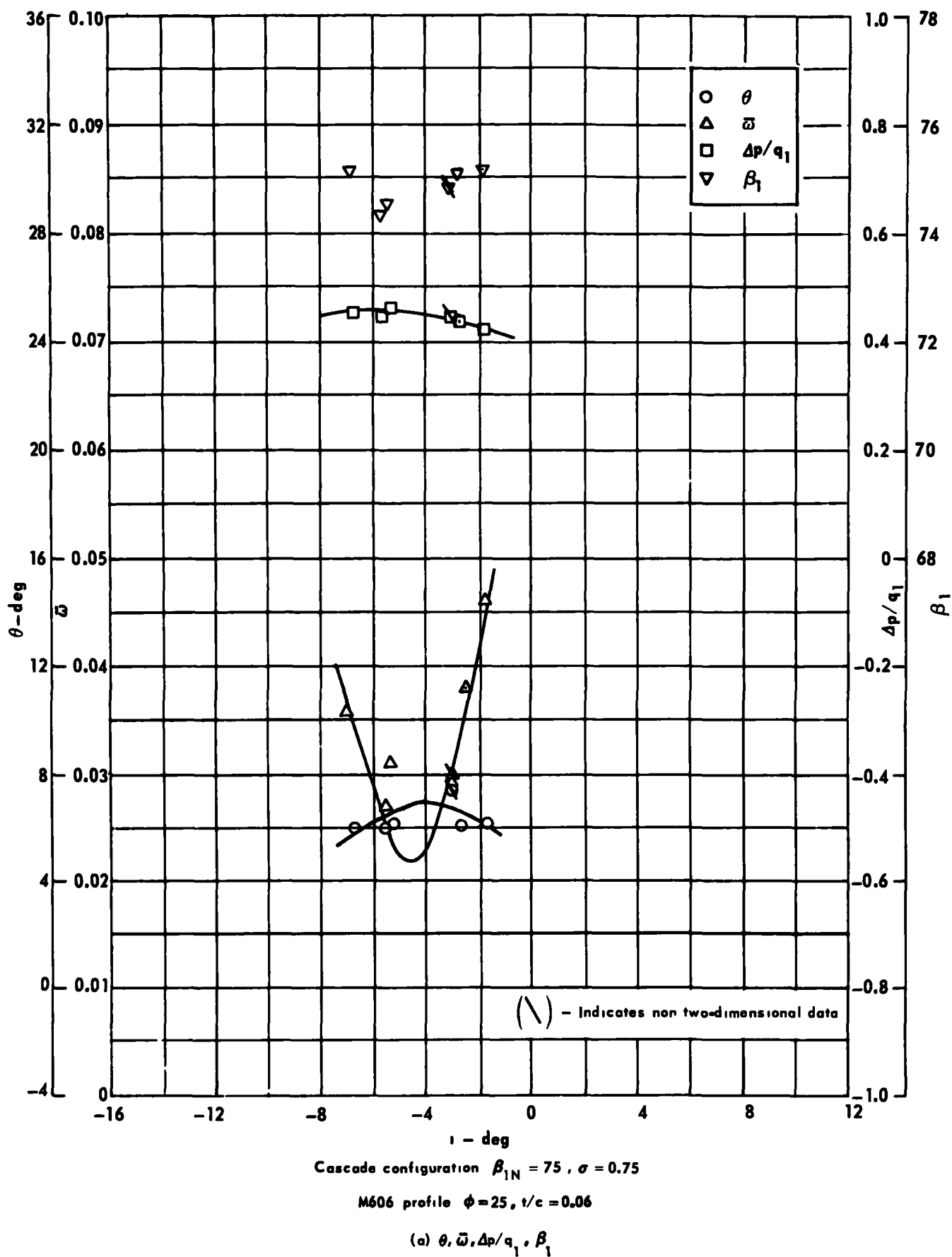
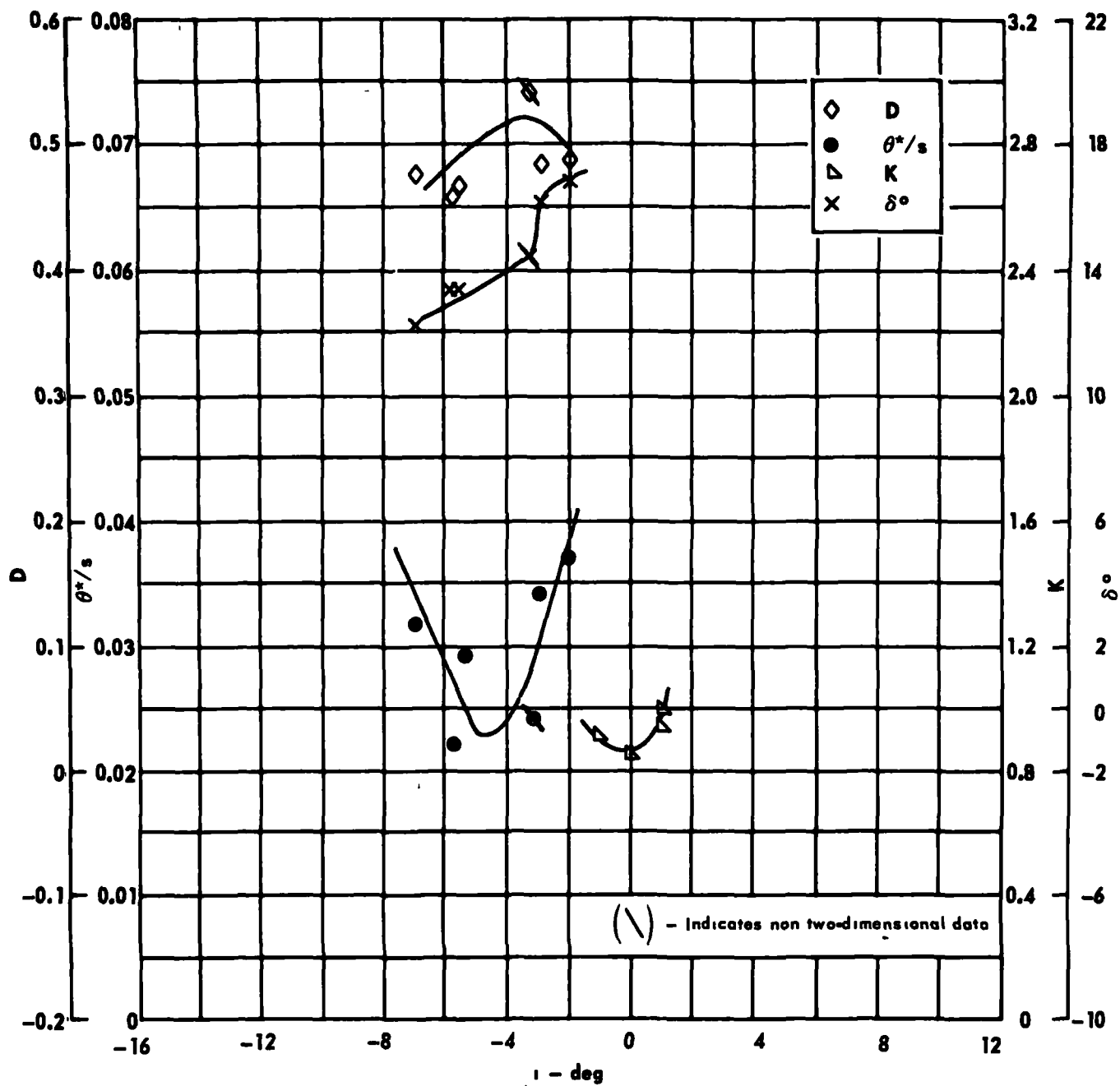


Figure 47 . - Cascade characteristics as functions of incidence.

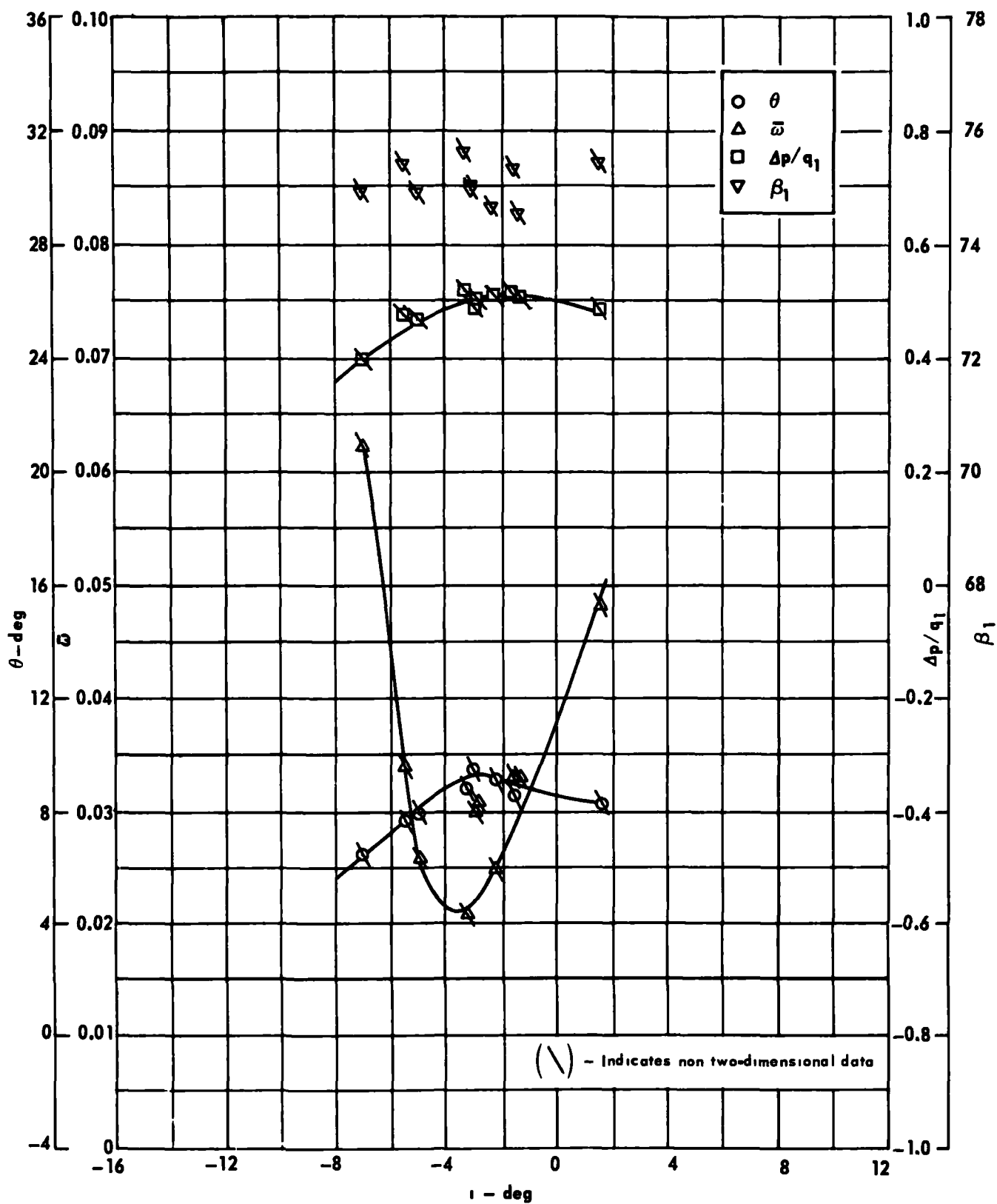


Cascade configuration $\beta_{1N} = 75, \sigma = 0.75$

M606 profile: $\phi = 25, t/c = 0.06$

(b) D, θ^*/s , K, δ°

Figure 47. - Concluded.

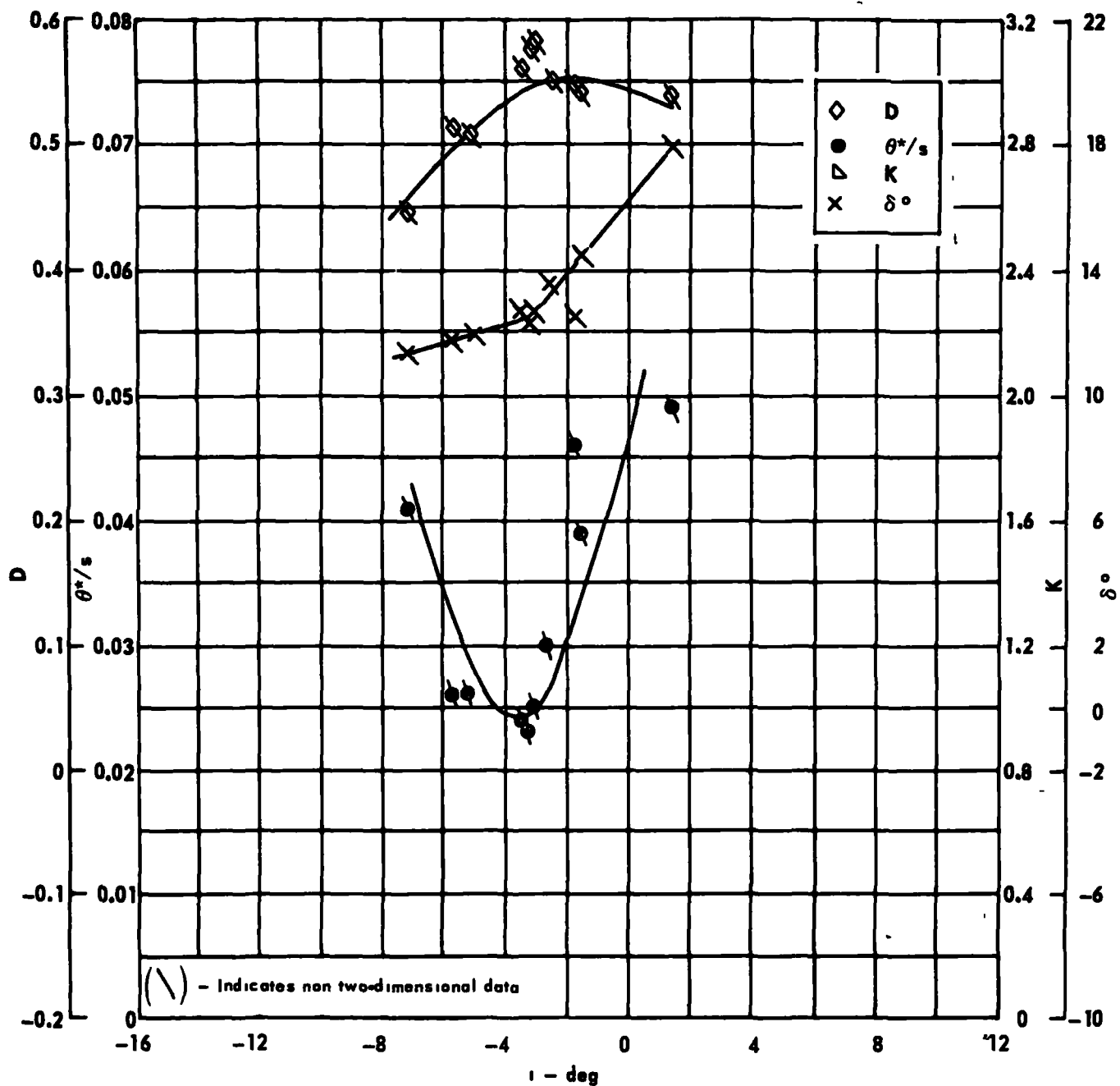


Cascade configuration $\beta_{1N} = 75$, $\sigma = 1.00$

M606 profile $\phi = 25$, $v/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 48. - Cascade characteristics as functions of incidence.

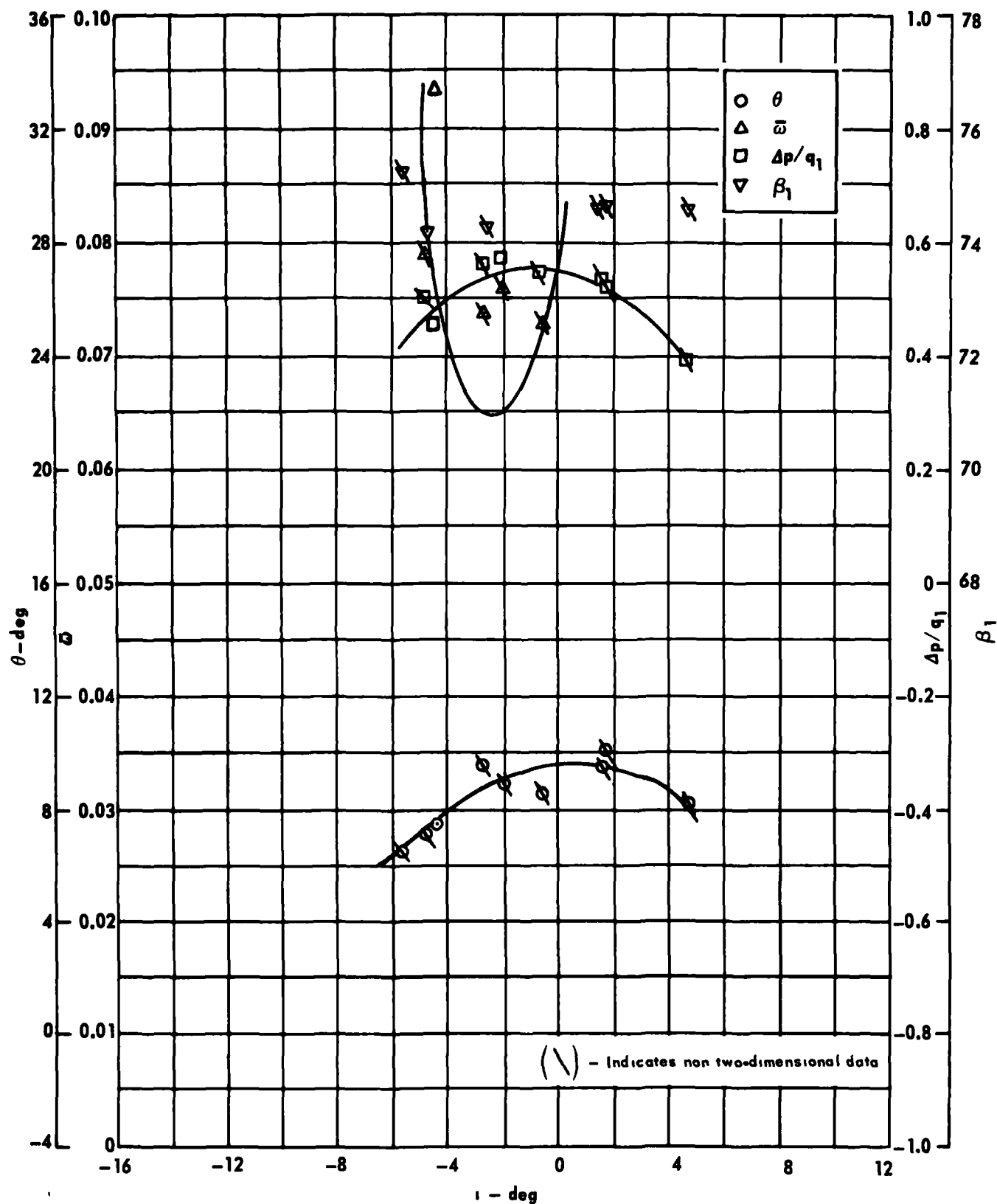


Cascade configuration $\beta_N = 75$, $\sigma = 1.00$

M606 profile: $\phi = 25$, $t/c = 0.06$

(b) $D, \theta^*/s, K, \delta^\circ$

Figure 48. - Concluded.



Cascade configuration $\beta_{1N} = 75$, $\sigma = 1.50$

M606 profile $\phi = 25$, $t/c = 0.06$

(a) $\theta, \bar{\omega}, \Delta p/q_1, \beta_1$

Figure 49. - Cascade characteristics as functions of incidence.

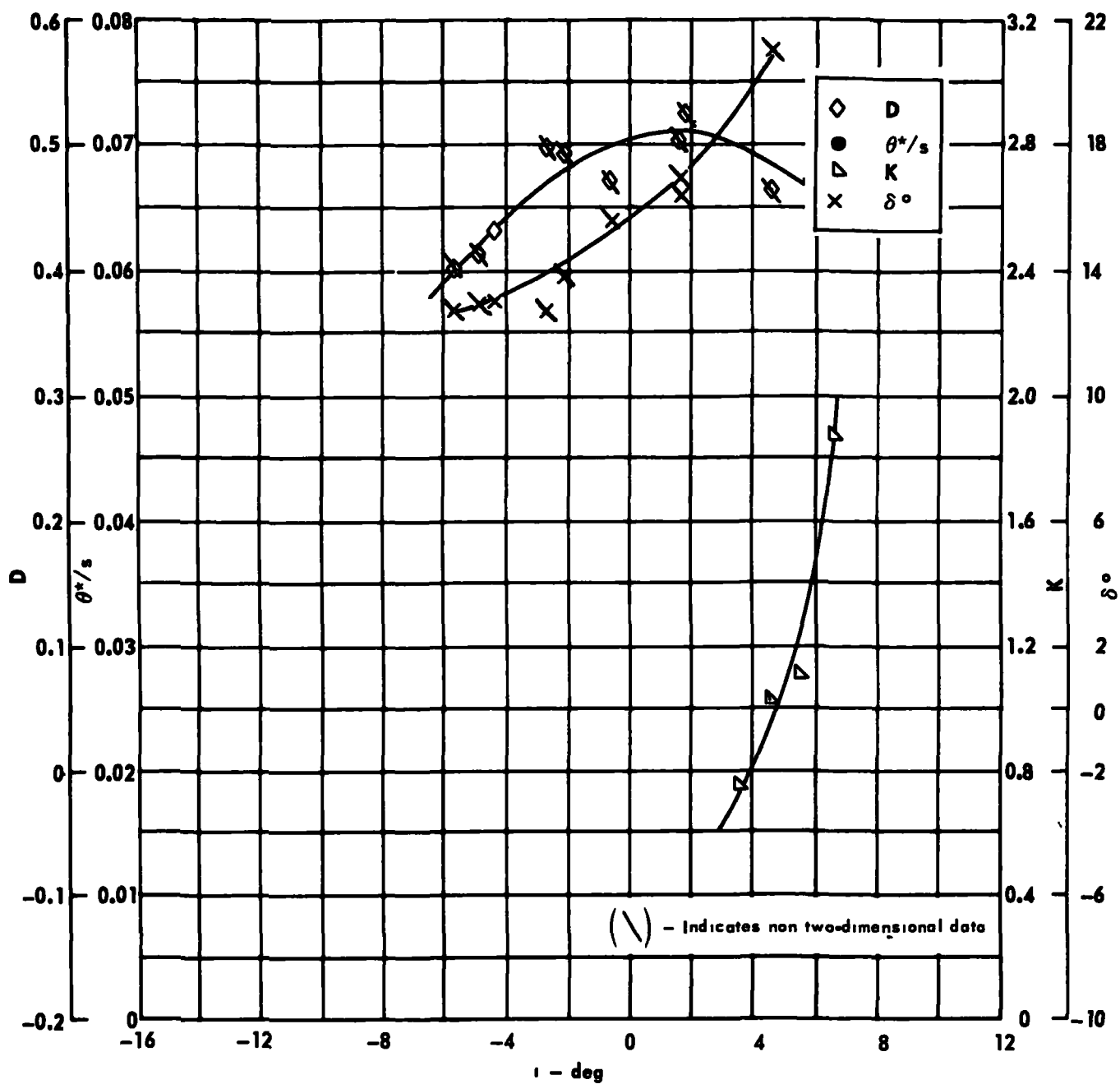
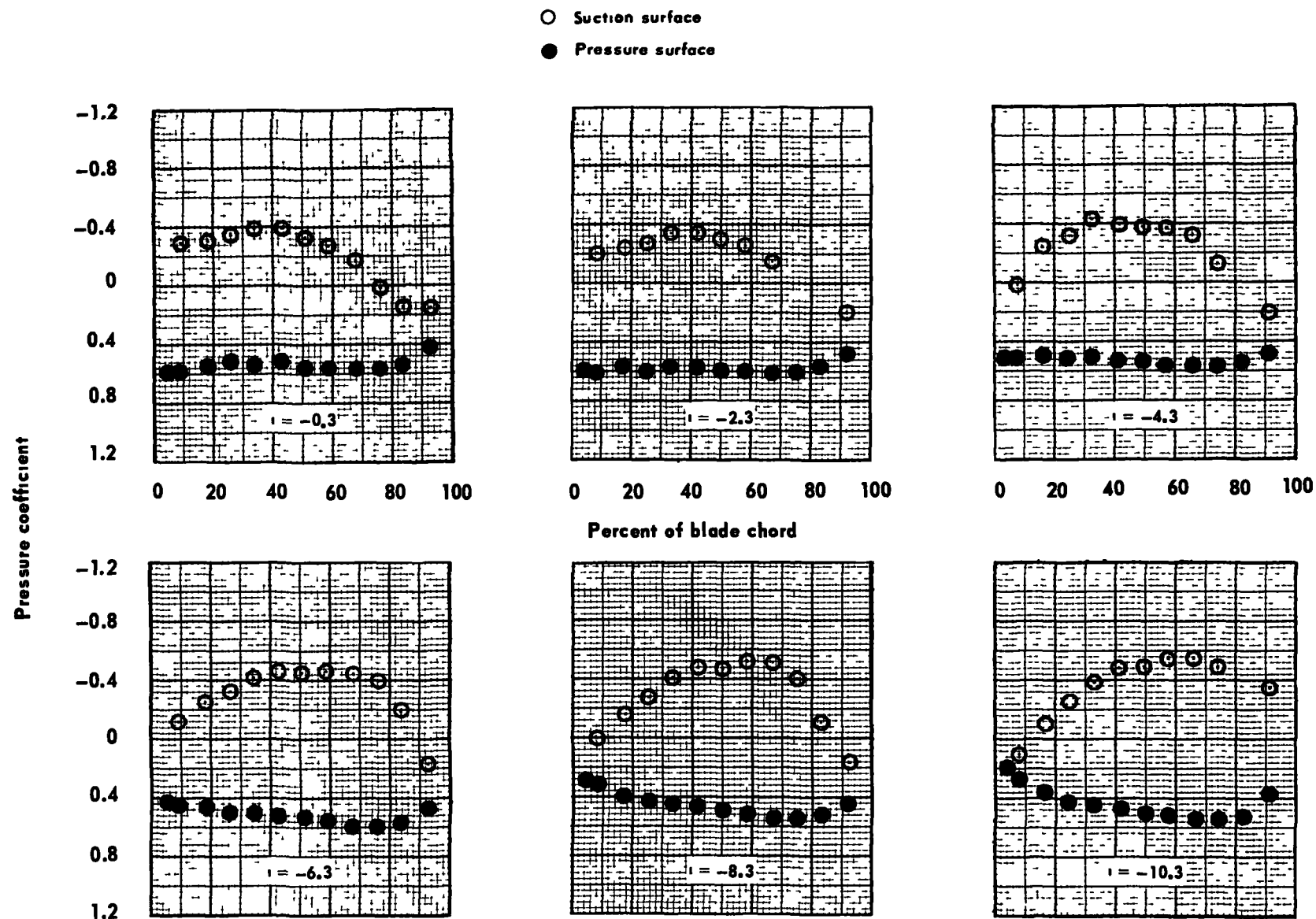


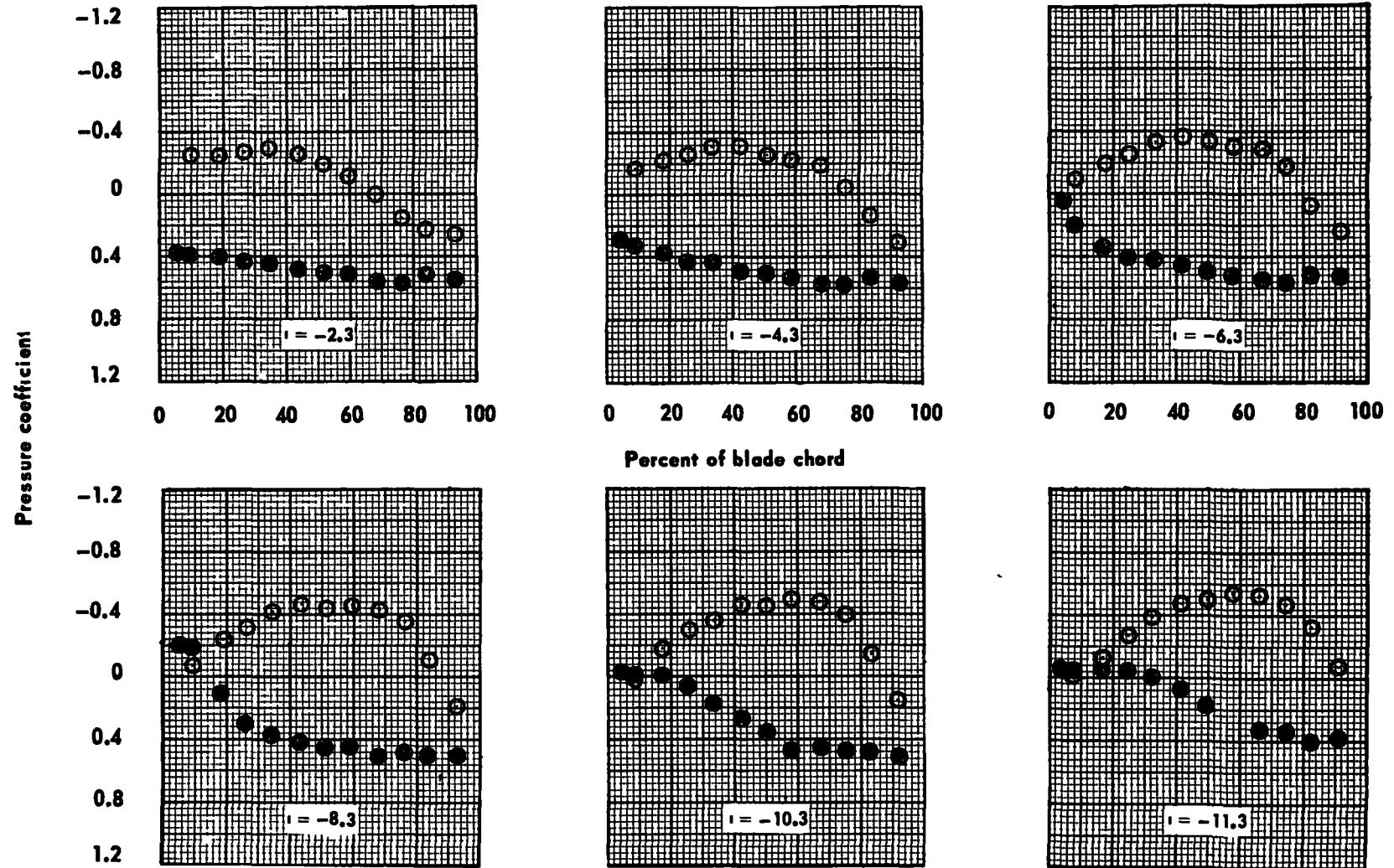
Figure 49. - Concluded.



(a) $\phi = 40$, $\beta_{1N} = 60$, $\sigma = 0.75$

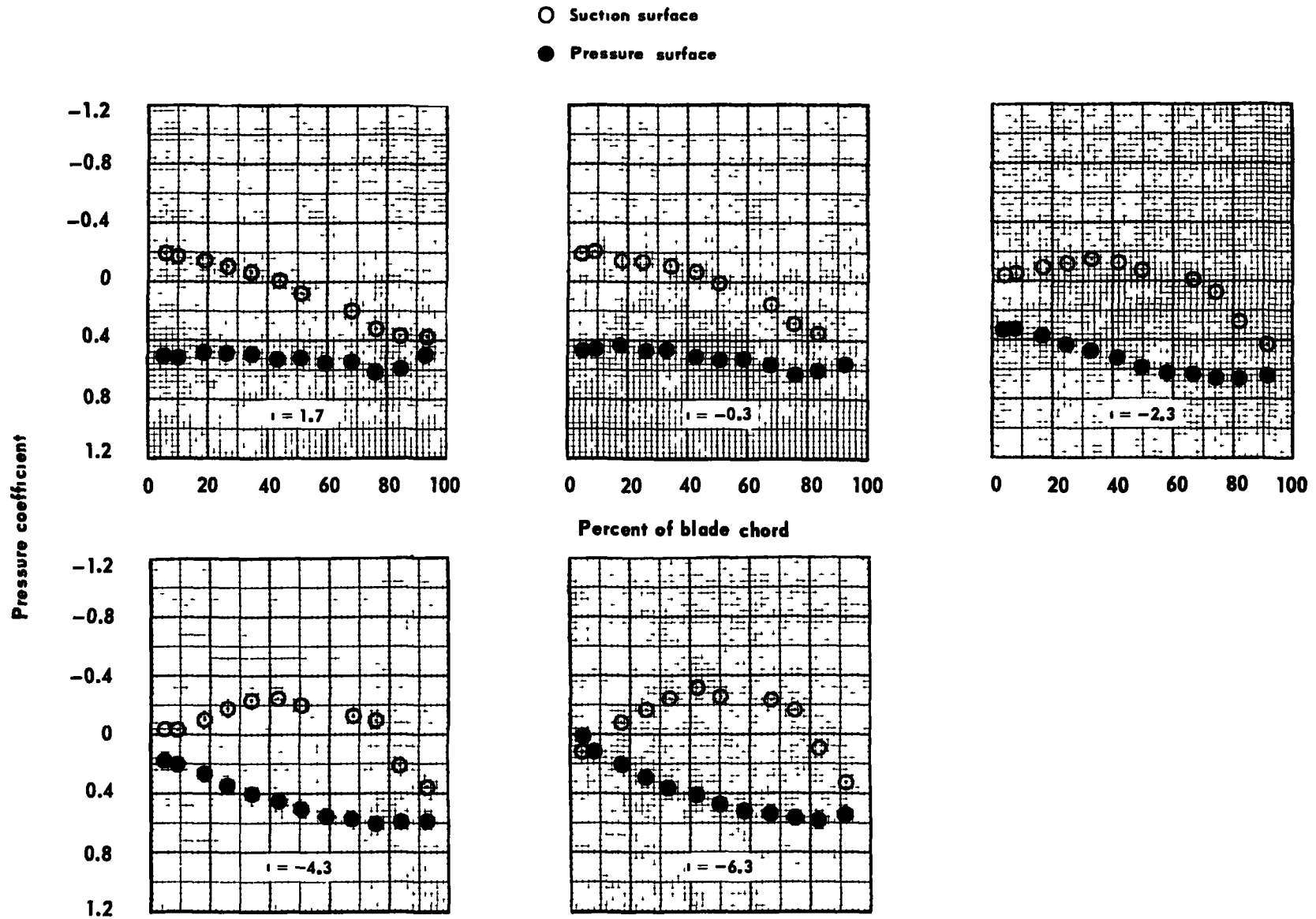
Figure 50. -NACA M606 hydrofoil pressure distributions.

○ Suction surface
● Pressure surface



(b) $\phi = 40$, $\beta_{1N} = 60$, $\sigma = 1.00$

Figure 50. - Continued.



(c) $\phi = 40$, $\beta_{1N} = 60$, $\sigma = 1.50$

Figure 50. - Concluded.

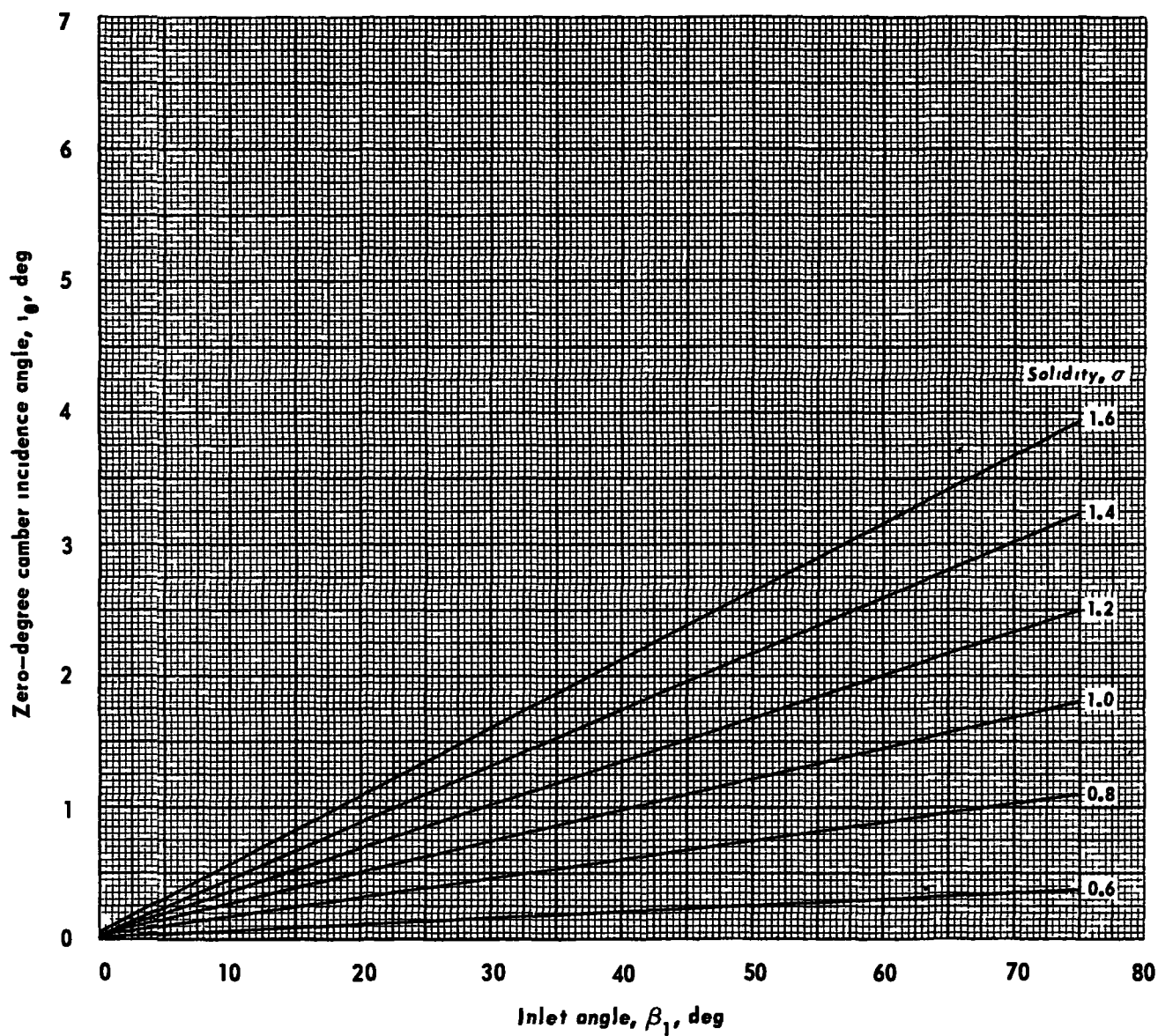


Figure 51 . - Reference minimum-loss incidence angle for zero-degree camber multiple circular-arc hydrofoils.

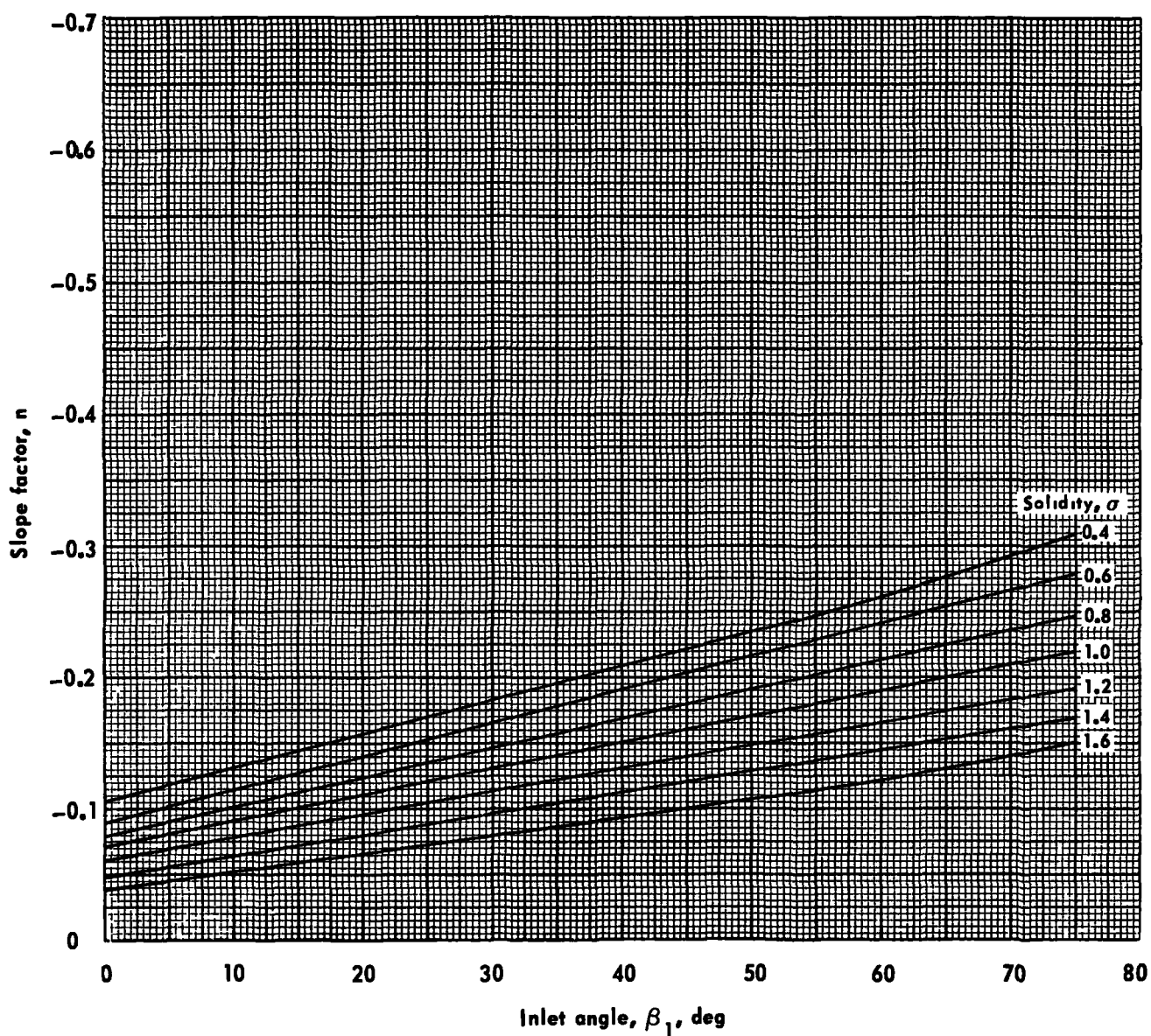


Figure 52. - Slope factor for reference minimum-loss incidence angle-multiple circular-arc hydrofoils.

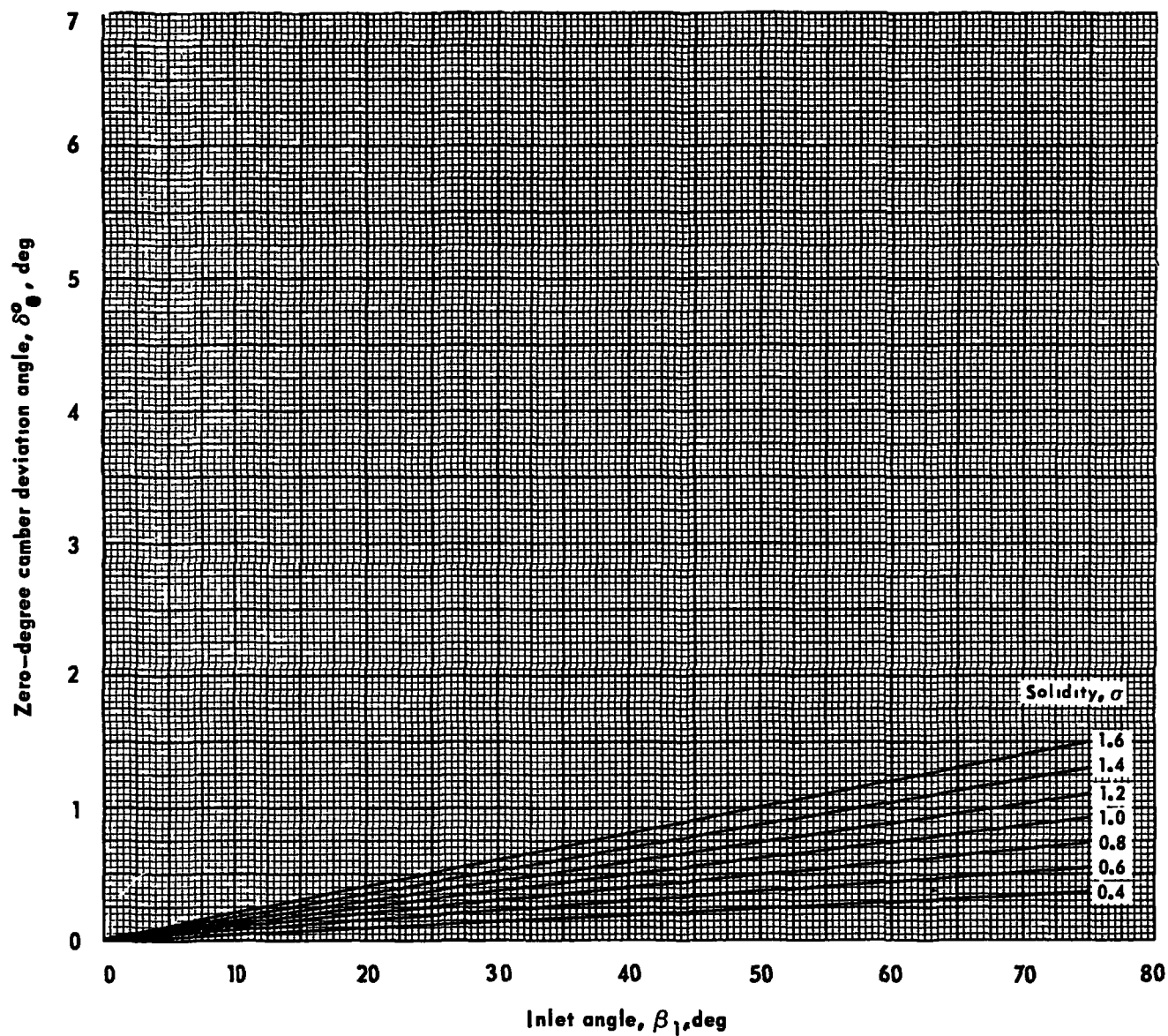


Figure 53. — Reference minimum-loss deviation angle for zero-degree camber multiple circular-arc hydrofoils.

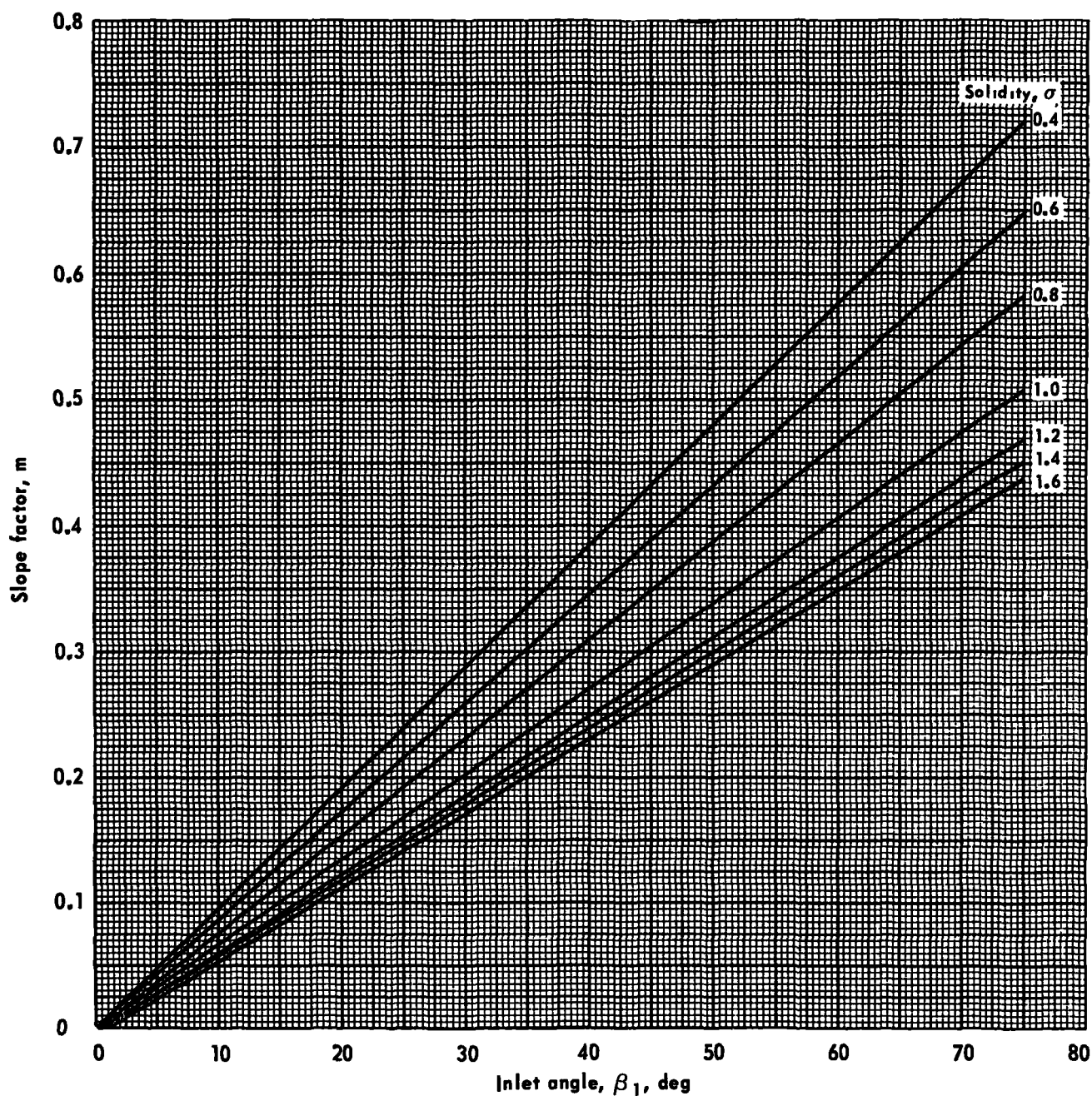


Figure 54. — Slope factor for reference minimum-loss deviation angle—multiple circular-arc hydrofoils.

MCA	Symbol	Solidity
Minimum -	○	0.75
loss'	△	1.00
points	□	1.50

Solid symbols Ref. 8

— M606 correlation

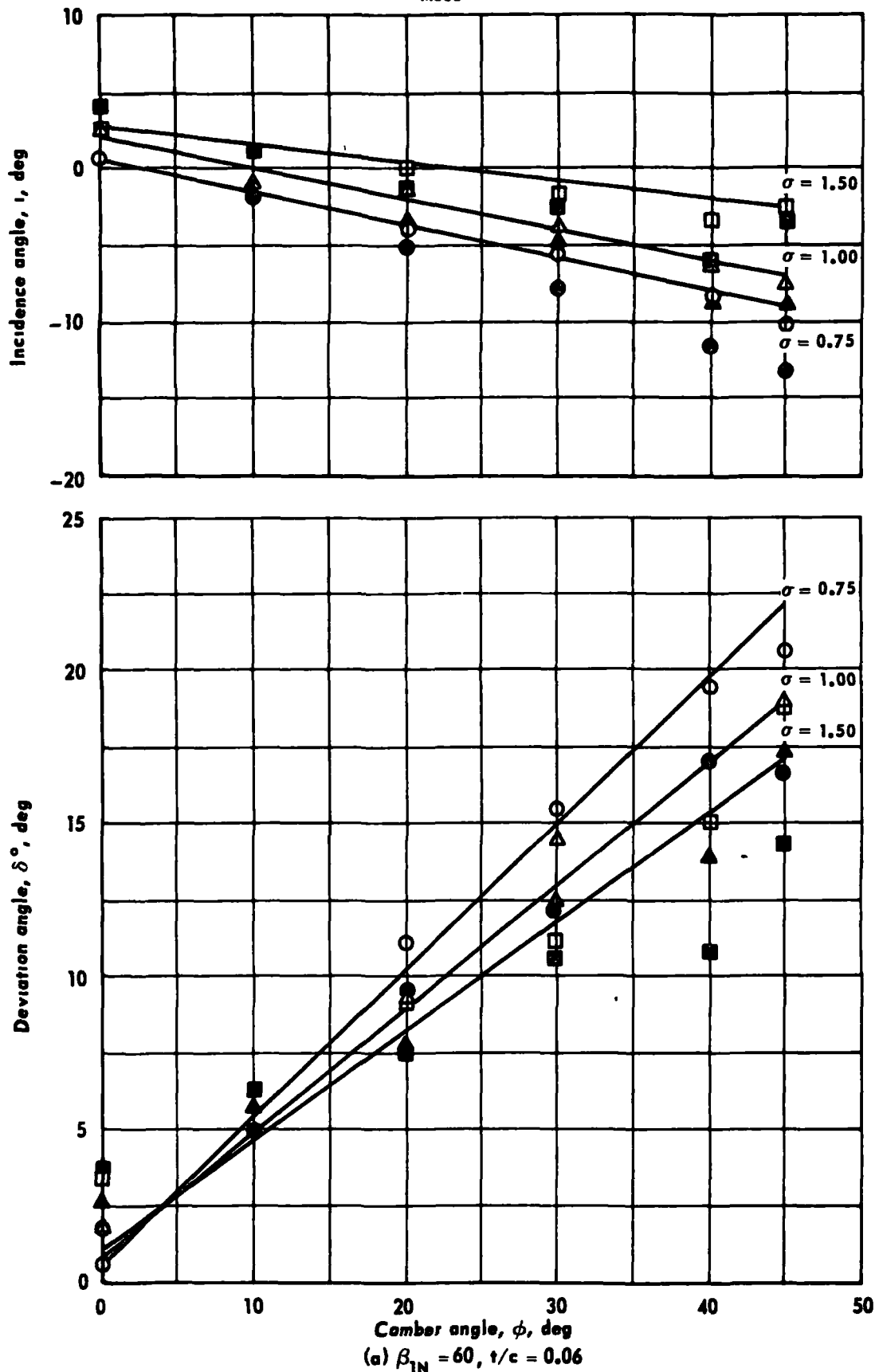


Figure 55. — Incidence and deviation angles for minimum total pressure loss coefficient.

MCA	Symbol	Solidity
Minimum - loss points	○	0.75
	△	1.00
	□	1.50

Solid symbols Ref. 8

— M606 correlation

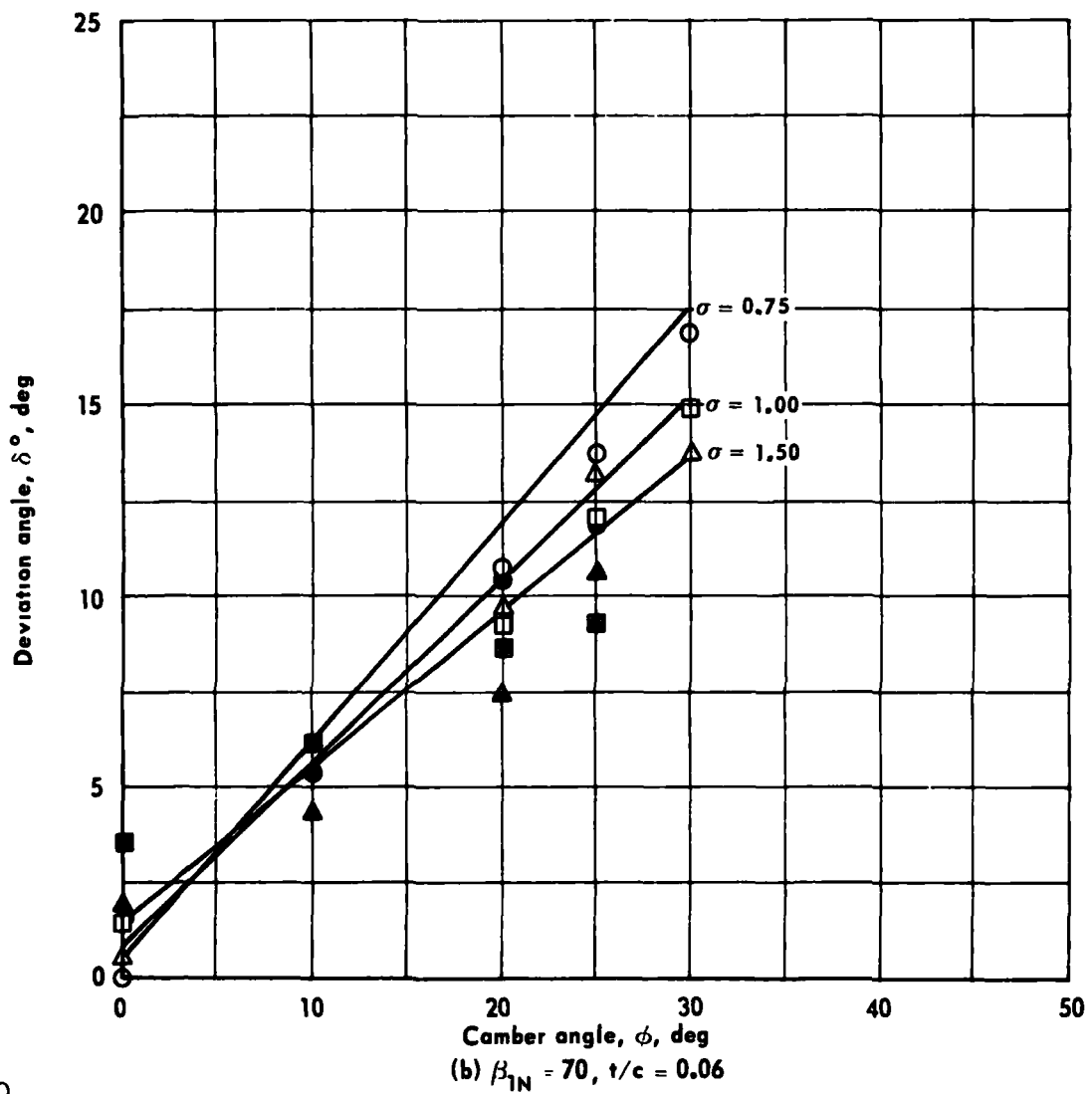
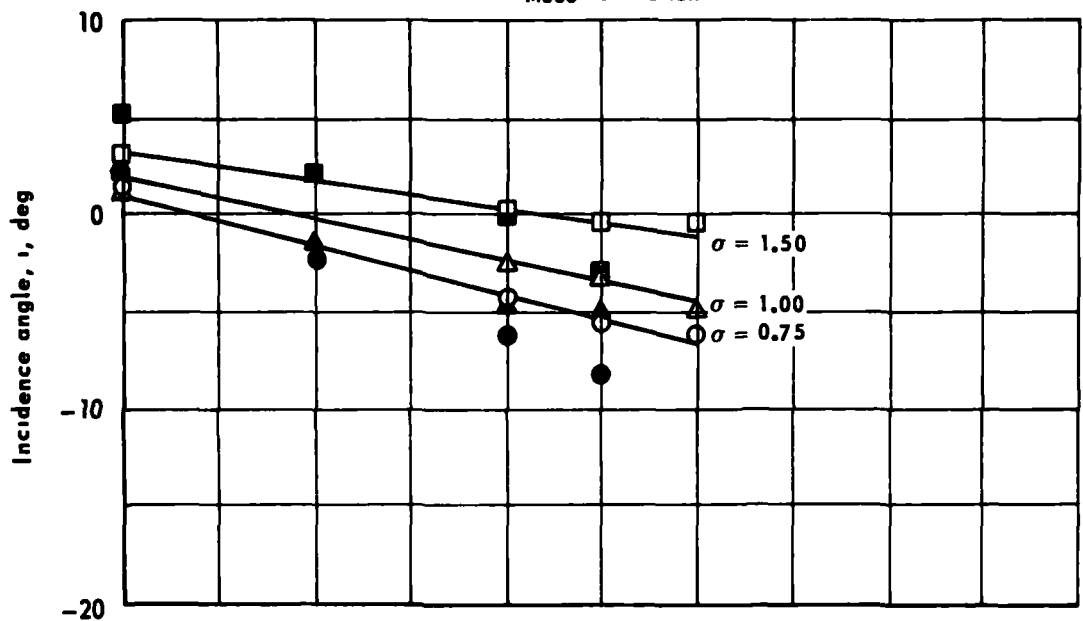
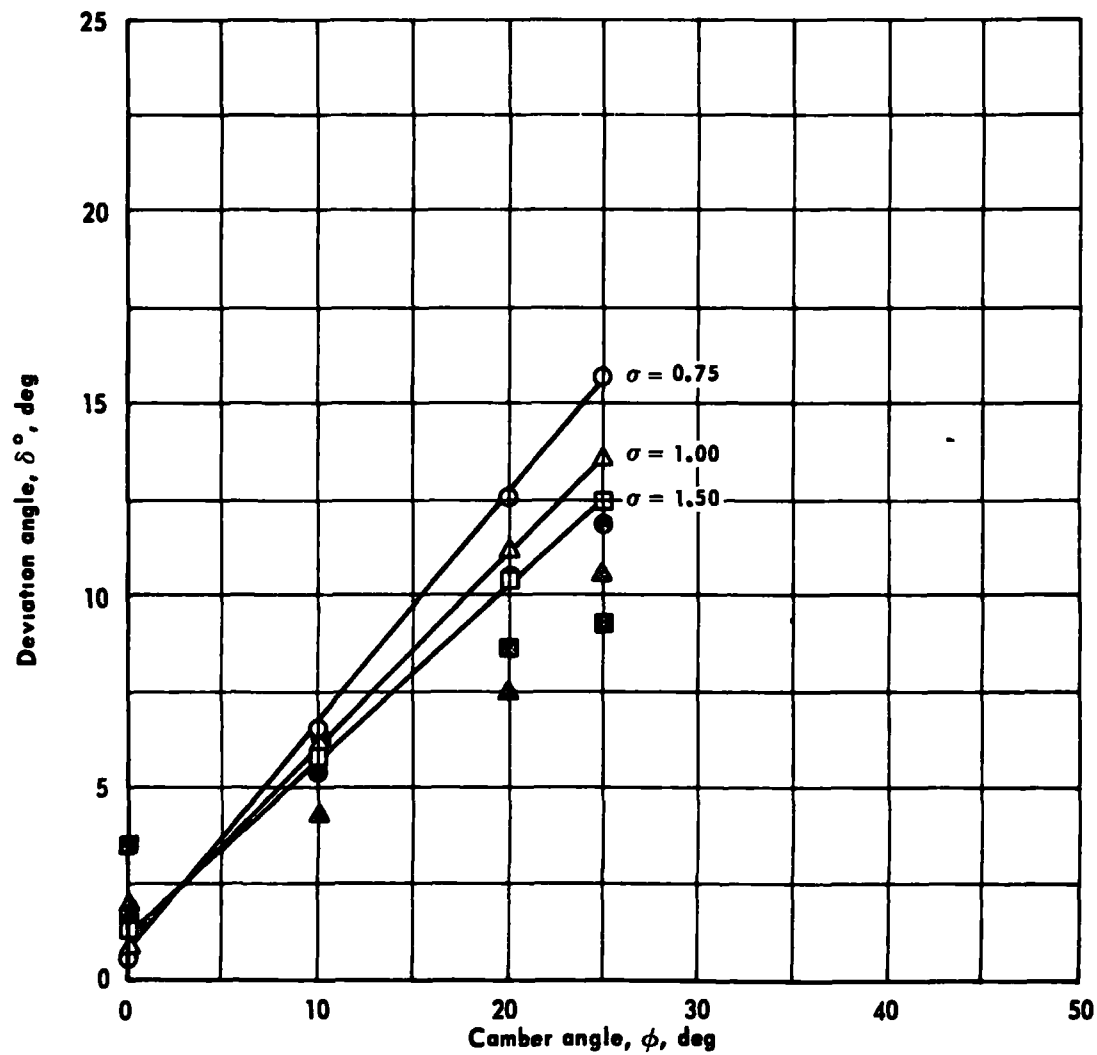
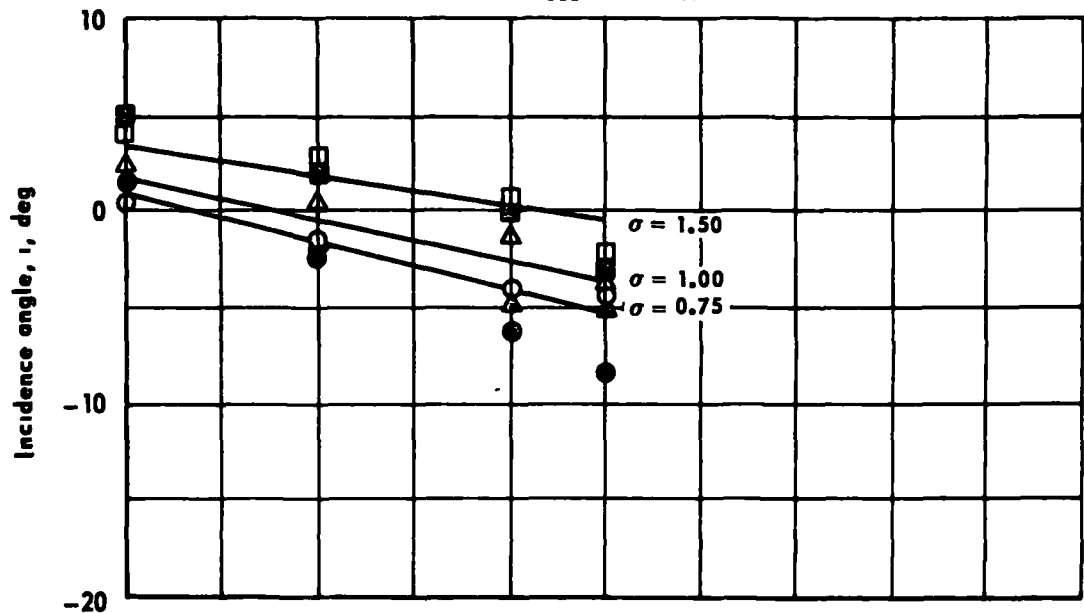


Figure 55. - Continued.

MCA	Symbol	Solidity
Minimum - loss points	○	0.75
	△	1.00
	□	1.50

Solid symbols Ref. 8

— M606 correlation



(c) $\beta_{1N} = 75$, $t/c = 0.06$

Figure 55. - Concluded.

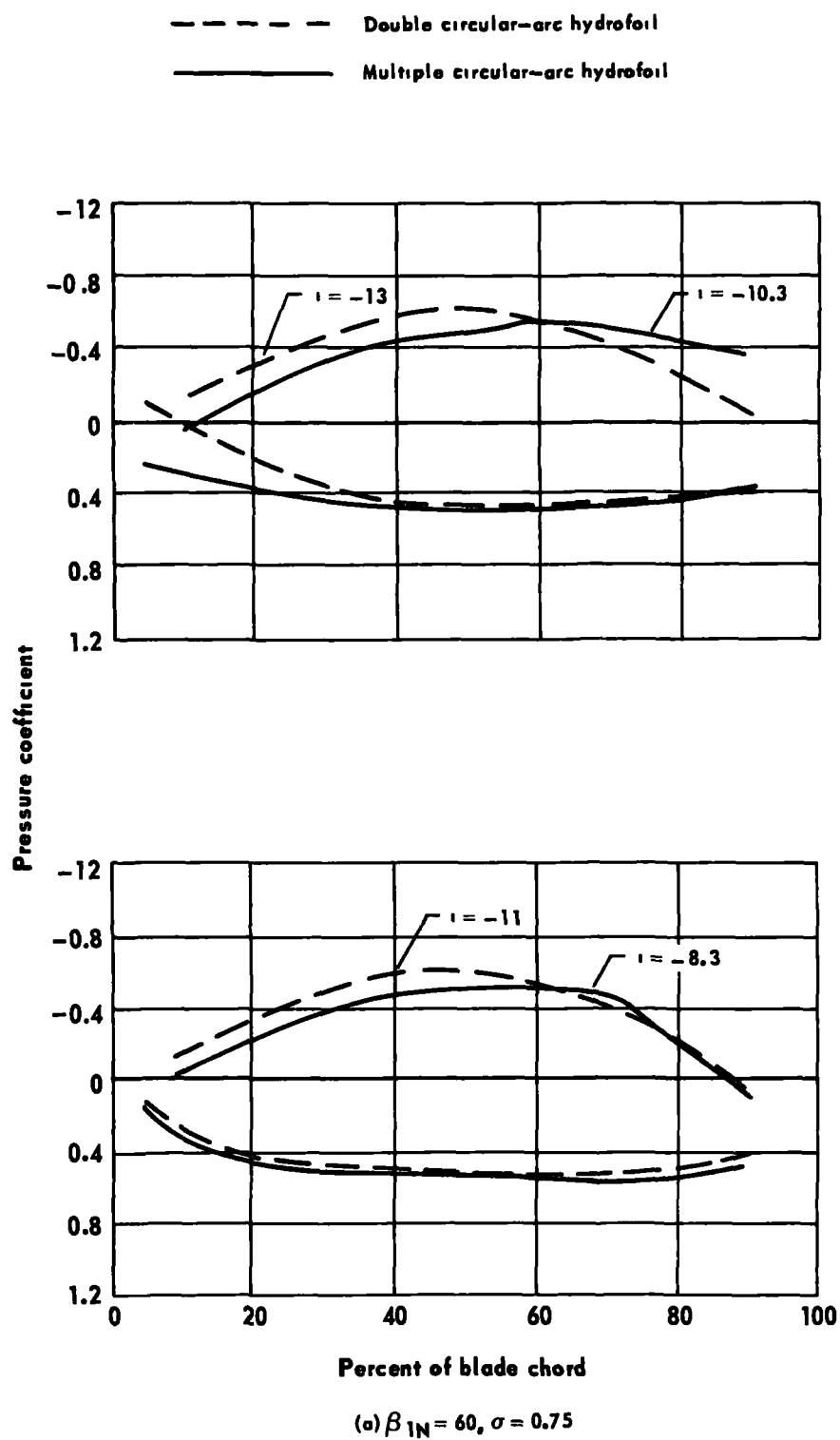


Figure 57. — A comparison of pressure distributions for 40 degree camber circular-arc hydrofoils.

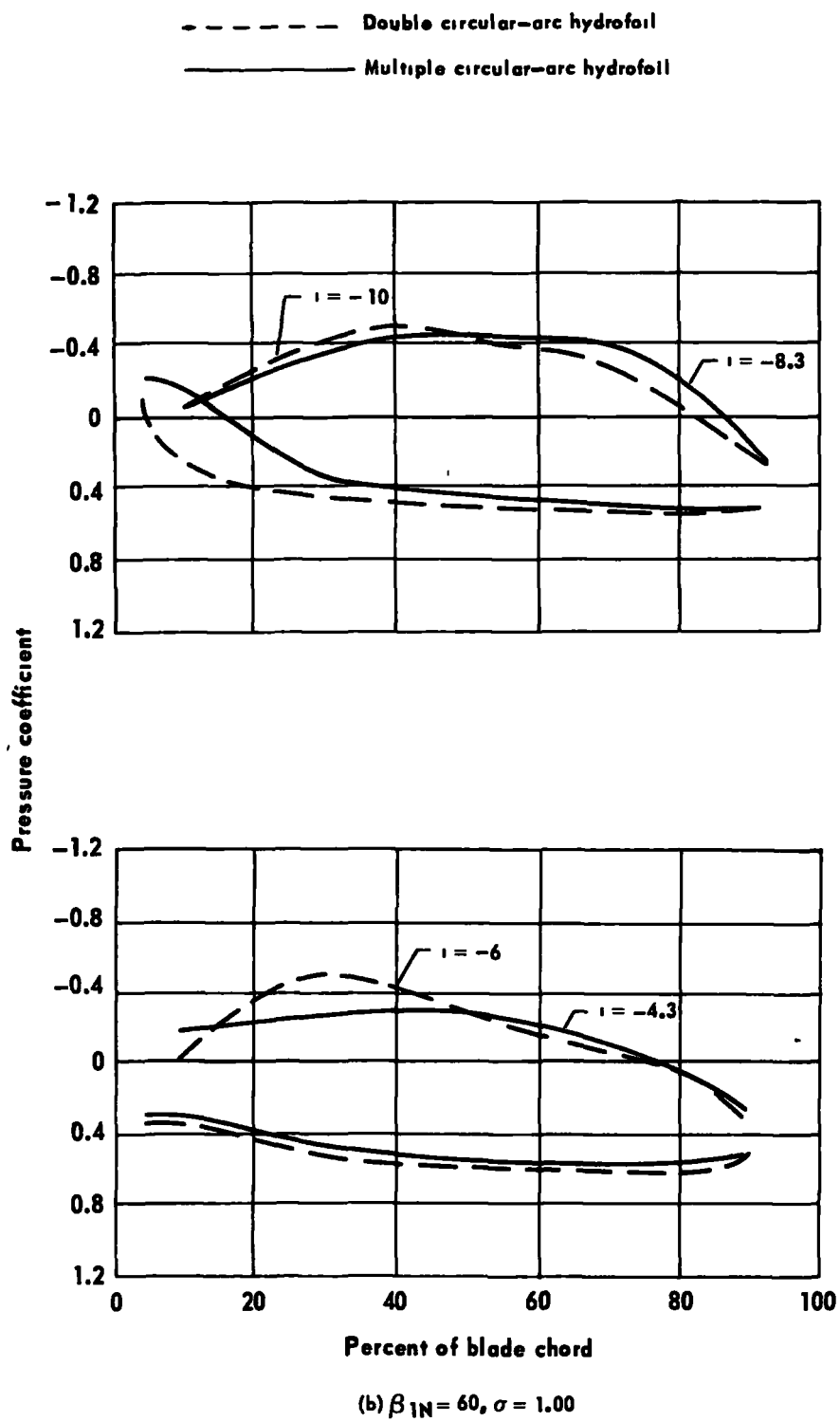
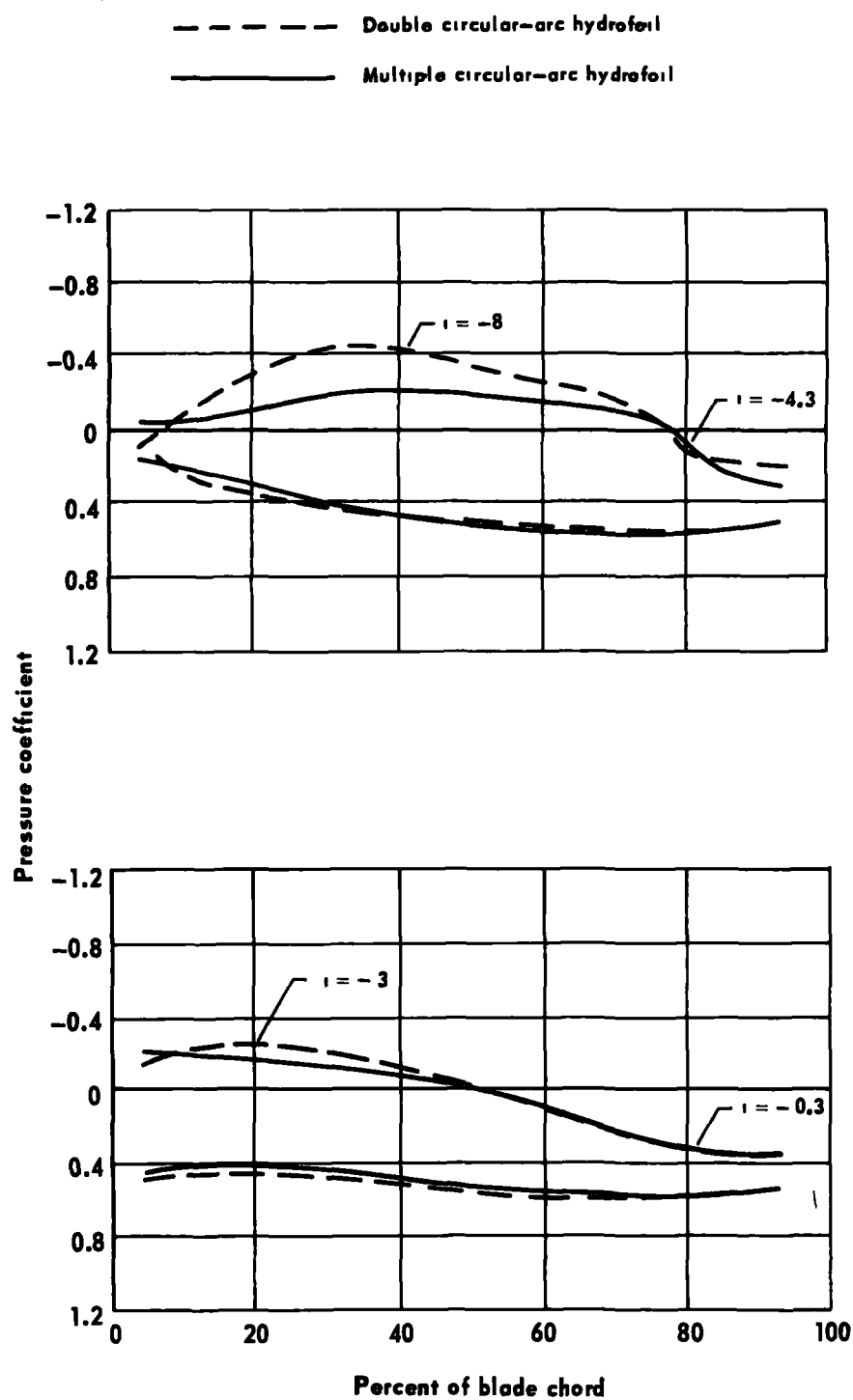


Figure 57. - Continued.



(c) $\beta_{1N} = 60, \sigma = 1.50$

Figure 57. — Concluded.

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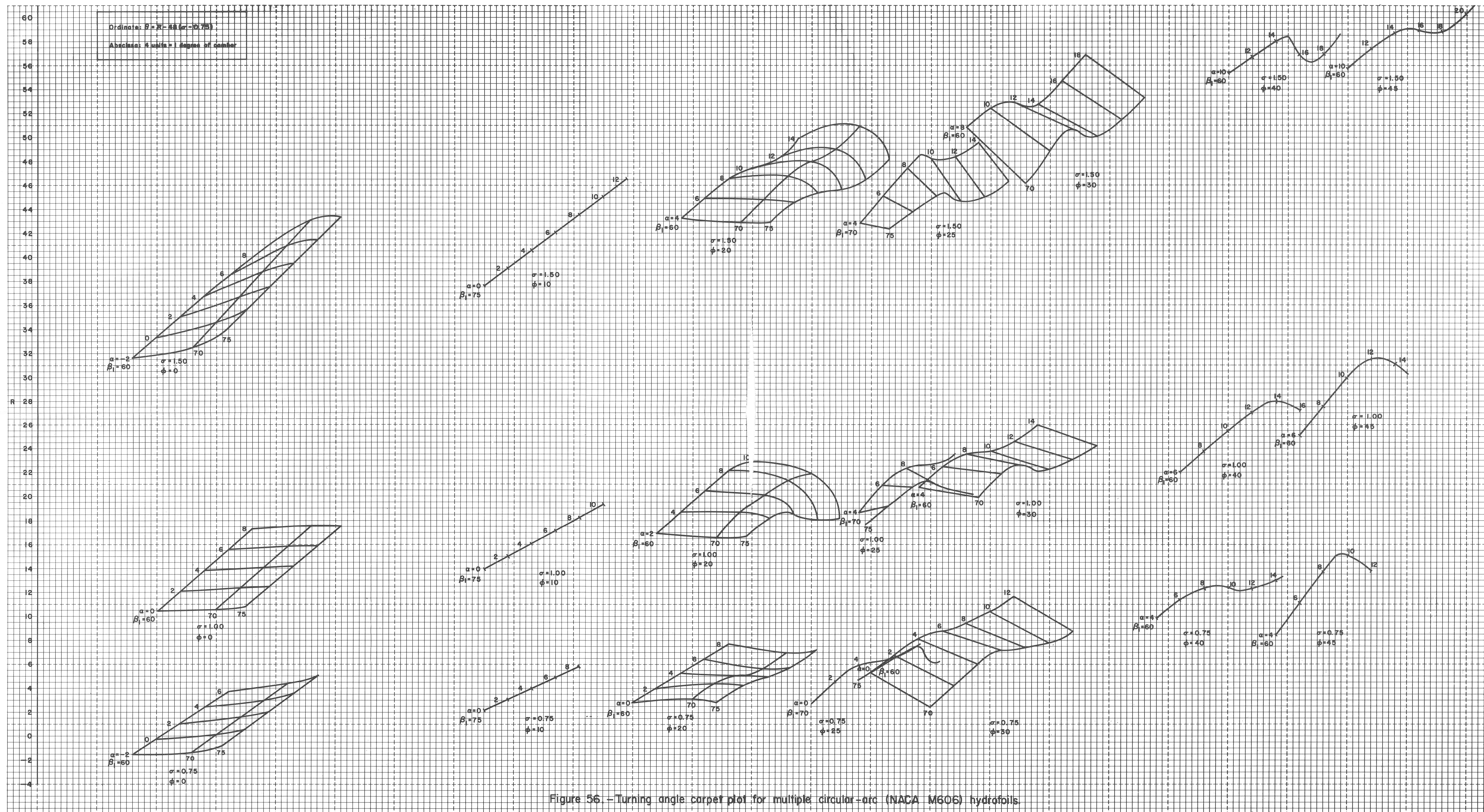


Figure 56. -Turning angle carpet plot for multiple circular-arc (NACA M606) hydrofoils.