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ABSTRACT

Methods to quantitatively determine the dynamic response of automatic ellipsometers to variations in the optical properties of a specimen have been developed and are illustrated by data from a newly-built ellipsometer. The quantities determined include slew-rate, frequency response, accuracy and resolution. The methods are based on the use of rotating mirrors for the generation of well-defined, fast optical changes in the reflecting surface.

I. INTRODUCTION

Automatic ellipsometers of different designs have recently been constructed for the observation of temporal changes on a reflecting surface,[1-4] and the use of such instruments in increasing numbers can be expected in the near future. The critical evaluation of results obtained with automatic ellipsometers, such as the identification of artefacts, as well as a comparison of capabilities between instruments of different design,[5] requires a knowledge of quantitative performance characteristics.

Parameters which characterize the capabilities of an automatic ellipsometer are the maximum rate of change (slew rate) and the maximum range of change (dynamic range) that can be followed automatically, the accuracy and reproducibility of following, the smallest variation that can be resolved (resolution), the specimen area required for reflection and some of the multiple interactions between these quantities.

In order to represent behavior under conditions of practical use, such performance characteristics should be determined with a reflecting surface that changes its optical properties predictably over a wide range of optical properties and rates of change. In the present work, the use of a reflecting disk which is rotated around an axis normal to its surface, has been introduced for this purpose. During rotation, the reflecting surface element traces a ring on the disk, and any variations in optical properties along this ring simulate a reflecting surface of optical properties varying in time.

Tests based on this principle can provide quantitative performance characteristics for automatic ellipsometers operating on different working principles and with a wide range of capabilities under conditions that closely reproduce actual use.

II. MIRROR PREPARATION

Different functional relations of relative phase and amplitude with time can be achieved by the use of rotating disk mirrors. Among these relations are irregular, gradual, saw-tooth, square-wave, single-step and sinusoidal variations. The latter two cases have been found most useful and are reported here. The mirrors have been prepared by vacuum deposition of an opaque metal substrate, followed by a thin film coating of a uniform thickness, on optical-quality round glass plates.[6]

Square-wave (or single-step) changes in optical properties have been produced by depositing a sharply delineated coating over half of a 76 mm diameter disk (Fig. 1a). A full rotation thus results in a downward and an upward step. Sinusoidal changes have been obtained with multiple segments of width comparable to the area sampled by the light beam (Fig. 1b). The coating material has been evaporated through a mask with precisely cut multiple openings held in good contact with the substrate. Figure 2 shows one of the test mirrors in use. Data on substrate and coating deposits employed are given in Table I.

III. ELLIPSOMETER ARRANGEMENT

Our test procedures are illustrated by results obtained with a newly-built compensating automatic ellipsometer[7] of design similar to that described by Layer.[4] The optical components are arranged for elliptic polarization incident on the specimen, and a quarter-wave plate of fixed +45° azimuth is used.[8] Faraday cells, inserted between polarizer and compensator as well as between specimen and analyzer, are employed to electrically rotate the plane of polarization over the dynamic range to either side of the mechanically established azimuths of polarizer and analyzer prisms. Analyzer and polarizer azimuth readings a and p at compensation are obtained by adding the electrical "angle readings" A and P to the manually established azimuth angles a_m and p_m of analyzer and polarizer prisms.

$$a = A + a_m \tag{1}$$

$$p = P + p_m \tag{2}$$

With ideal optical components, the change in relative phase Δ and the amplitude parameter ψ of the reflection as determined in one zone are[9]

$$\Delta = 270° - 2p \tag{3}$$

$$\psi = a \tag{4}$$

The angle of incidence was 75°, the light beam was of rectangular cross-section, 1×3 mm, and resulted in an area of approximately 4×3 mm being sampled on the reflecting surface.

IV. RESPONSE TO STEP-WISE CHANGES

An important characteristic of an automatic ellipsometer is its response to a discontinuous (or very fast) change in the optical parameters to be measured. Properties that can be determined from the response include the slew-rate, any possible overshoot, the symmetry of response in upward and downward direction and the influence of step height on the response.

Although sharp boundaries on the mirror can relatively easily be produced by vapor deposition, the finite width of the light beam results in a more gradual change in the measurement. For a given rate of rotation, the fastest change is obtained by orienting the step of the deposit in a radial direction and minimizing the extent of the sampled area normal to the step. Thus, at 300 rpm an ideally sharp step on a 32 mm radius moves through a 4 mm wide sampling area in 4 ms.

The accuracy of dynamic response for a given step-height is obtained by comparison with static measurements, (which agree with manual measurements) (Fig. 3). The test is conducted by observing the output of the instrument at different rotation rates of the mirror (Fig. 4). At increased rates of rotation, the slope of the step is limited by the capabilities of the instrument and deviates from the slope expected on the basis of static measurements (Fig. 5). Thus, a limiting slew-rate (maximum rate of rotation of polarizer and analyzer azimuths) of 1.6°/ms has been established for our ellipsometer.

V. RESPONSE TO SINUSOIDAL CHANGES

An alternate way to characterize an automatic ellipsometer consists in the frequency response of the instrument to sinusoidal variations in the properties of the reflecting surface.

A rotating mirror surface with optical properties varying in a sinusoidal way could be approximated by vapor deposition with diffuse edges. In order for the light beam to sample a resonably uniform reflecting surface, each oscillation period on the mirror would have to be several times as wide as the sampled area, and high-frequency oscillations would be difficult to achieve. Instead, we have employed a rotating mirror with sharply delineated alternate deposits, illustrated in Fig. 1b, which are quite easily produced and provide the desired frequencies with manageable mirror diameters and rotation rates. With the individual mirror segments just slightly wider than the area sampled by the light beam, the mixed polarization, that results from reflection on two different materials during most of a cycle, produces an approximately sinusoidal variation in analyzer and polarizer azimuth.[10] Accuracy of tracking for slow variations is again demonstrated by the agreement with static measurements (Fig. 6).

With increasing frequency of the sinusoidal signal, the amplitude response of the instrument decreases (Fig. 6). The frequency at which a partial response sets in depends on the magnitude of the amplitude, as illustrated in Fig. 7. Thus, a 3.6° peak to peak signal has been found to be recorded at frequencies up to 160 Hz. Oscillations of amplitude greater than the dynamic range of the instrument (presently 51° for A and 55° for P) are tracked at higher frequencies with reduced amplitude.

VI. ACCURACY

In addition to closely reproducing static measurements, taken immediately before or after a dynamic measurement and demonstrated in Figs. 3, 4 and 6, an automatic ellipsometer should show no long-term drifts as may be due to variable conditions of the surroundings, warm up and aging of components, etc.

In our instrument, such drifts could easily be detected by comparing a manual with an automatic measurement on a specimen, that does not change its properties during the measurements. Drifts thus observed over a two-month period have been less than ±0.01° in azimuth readings of polarizer and analyzer. For other instruments it may be necessary to use a reflecting surface with long-term stability[11] to conduct such tests.

Another factor that determines accuracy is the cross-modulation between analyzer and polarizer channels. Automatic ellipsometers of different designs differ greatly in the susceptibility to this potential source of error. For our instrument, the cross-modulation could be determined with a stationary reflecting surface by observing the output of one channel (e.g., analyzer) while the output of the other channel (e.g., polarizer) was varied over the entire dynamic range by the mechanical rotation of one of the prisms (e.g., polarizer). Thus, azimuth changes of 5° and 50° in one channel have been found to affect the other channel by less than ±0.002° and ±0.02°, respectively.

VII. RESOLUTION

The smallest short-term variation in the optical properties of a reflecting surface that can be resolved by an ellipsometer is usually limited by noise in the electric circuit. For many automatic ellipsometer configurations, resolution can be increased at the expense of speed of response. It is therefore of interest to extablish to what extent the resolution can be increased and how such an increase affects the transient capabilities. For the present instrument, this relationship is illustrated in Figs. 8-10. Figure 8 shows how increasing the time-constant from the normal value of about 1 ms changes the response to a step-wise signal. The improvement in resolution that can be obtained by slower operation is summarized in Fig. 9. For example, with a time-constant of 0.1 s, changes in analyzer and polarizer azimuth of 0.0007° can be resolved on a single step mirror rotating at less than 2 rpm. The slew-rate for response to a step-wise change is then 0.33°/s. As a further characterization of the effect of integration time, the frequency response in different slow modes of operation is given in Fig. 10. With a time constant of 10^{-2} s, a peak to peak signal of 0.22° is fully recorded at frequencies up to 30 Hz. Below 0.01°, the resolution of the mechanical polarizer and analyzer circles, azimuth readings can only be interpreted as differences relative to other observations.

VIII. CONCLUSIONS

The use of rotating mirrors offers a convenient way to characterize the response of an automatic ellipsometer to changes in relative phase and amplitude as a function of time. Since the changes originate in the reflecting surface, the measurements represent the response of the entire automatic system. Widely different response times and dynamic ranges can easily be accommodated.

Apart from the presently-used variation in relative phase and amplitude, the effect of other variables of a reflecting surface (e.g., reflectivity or surface roughness) on the response of the ellipsometer can be investigated. Similarly, rotating mirror surfaces may be useful for characterizing the dynamic response of reflection spectroscopic instruments, including spectroscopic ellipsometers.

As with any servo-system, the response of our automatic ellipsometer depends on all the factors that affect the gain in the electronic control-loop. The principal factors are photomultiplier voltage, light beam diameter and intensity, reflectivity and uniformity of the reflecting surface. Realistic values for these parameters, used in practical measurements, have been employed for the tests reported here.

ACKNOWLEDGEMENTS

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4. H. P. Layer, Surf. Sci. 16, 177 (1969).
5. R. H. Muller, in Advances in Electrochemistry and Electrochemical Engineering, Vol. 9, R. H. Muller, ed. (Wiley-Interscience, New York, 1973), p. 208.
6. Parallelo-plate, 9.5 mm thick, 76.2 and 190.5 mm diameter.
7. Accepted for publication by Rev. Sci. Instr. (also report LBL-1478, July 1973).
8. Reference 5, p. 200
9. Reference 5, p. 212.
10. Due to the mixed (partial) polarization of the reflected light, only partial extinction can be obtained at compensation. It is a credit to the functioning of the instrument that its response is not affected by this factor: Based on a slew-rate of 1.6°/ms, one would expect a frequency response of 142 to 222 Hz for a 3.6° peak to peak signal, depending on whether the steepest or the average slope of a sinusoidal variation is considered limiting. The observed response was 160 Hz (Fig. 7).
11. Reference 5, p. 215.
12. Decreased signal amplitudes of mirror No. 4 were produced by increasing the diameter of the light beam. The reflecting areas sampled were 4×4 to 5×10 mm.
13. Additional external filtering of the ellipsometer output with time-constant of 0.1 s was employed for curve d.

Table I. Properties of rotating mirrors.

				Substrate				With Coating			
No.	Diameter (mm)	Segments	Signal	Material	Thickness (nm)	ψ	Δ	Material	Thickness (nm)	ψ	Δ
1	76.2	2	Step	Cr	300	27.64	88.74	Al_2O_3(+Cr)	86	51.20	30.54
2	76.2	2	Step	Ag	200	45.60	86.20	Au(+Ag)	6.5	44.45	82.84
3	190.5	90	Sinusoid	Cr	300	25.28	88.40	Al_2O_3(+Cr)	70	74.08	339.00*
4	190.5	90	Sinusoid	Ag	200	44.85	81.16	Au(+Ag)	10	41.39	76.32
5	190.5	90	Sinusoid	Cr	300	24.47	89.92	Al_2O_3(+Cr)	20	34.12	62.64

Note: Δ and ψ determined with Eqs. (3) and (4) from measurements in one zone.

*Δ = 630°-2p

FIGURE CAPTIONS

Fig. 1. Rotating disk mirrors for producing known variations in relative phase and amplitude of reflecting light.

A - substrate, B - coating, C - area sampled by light beam.

(a) Disk for step-wise variations.

(b) Disk for sinusoidal variations.

Fig. 2. Rotating disk mirror (No. 3) positioned in automatic ellipsometer.

A - Polarizer circle

B - Polarizer Faraday cell

C - Compensator circle

D - Disk mirror with drive motor

E - Analyzer Faraday cell

Light propagation from A to E.

Fig. 3. Dynamic and static response to a step-wise variation in polarizer and analyzer azimuth. Mirror No. 1, 300 rpm, $p_m = 105°$, $a_m = 35°$

Fig. 4. Response to an increasingly fast step-wise variation in polarizer azimuth. Mirror No. 1, $p_m = 108°$. Points indicate static measurements, lines indicate dynamic measurement at (a) 67 rpm, (b) 275 rpm, (c) 650 rpm.

Fig. 5. Determination of the slew-rate as the limiting slope of the response to a step-wise variation (upward and downward) of polarizer and analyzer azimuth.

▲Analyzer, step height 20°, mirror No. 1
△Analyzer, step height 1.15°, mirror No. 2
Polarizer, step height 30°, mirror No. 1
□Polarizer, step height 1.8°, mirror No. 2

Fig. 6. Response to an increasingly fast sinusoidal variation in analyzer azimuth. Mirror No. 3, $a_m = 45°$. Points indicate static measurements, lines indicate dynamic measurements at (a) 13 rpm, (b) 45 rpm, (c) 204 rpm.

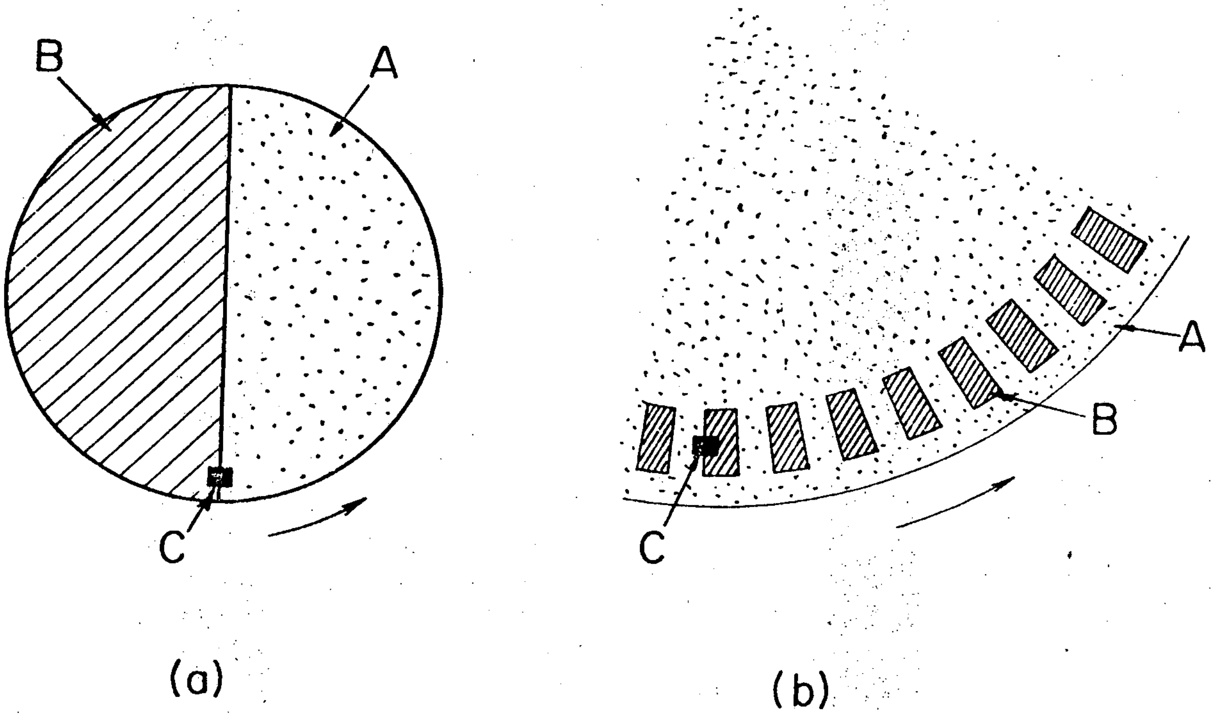
Fig. 7. Peak-to-peak amplitude response to sinusoidal variations in polarizer and analyzer azimuth of different emplitude.

(a) Analyzer, mirror No. 3
(b) Analyzer, mirror No. 3
(c) Analyzer, mirror No. 3
(d) Polarizer, mirror No. 5
(e) Analyzer, mirror No. 5
(f) Analyzer, mirror No. 4

Fig. 8. Effect of time-constant on the response to a step-wise variation in polarizer azimuth. Rotation rate 60 rpm, mirror No. 1, $p_m = 104°$. Time-constants: (a) 1×10^{-3} s, (b) 2×10^{-3}s, (c) 5×10^{-3}s, (d) 1×10^{-2}s, (e) 5×10^{-2}s.

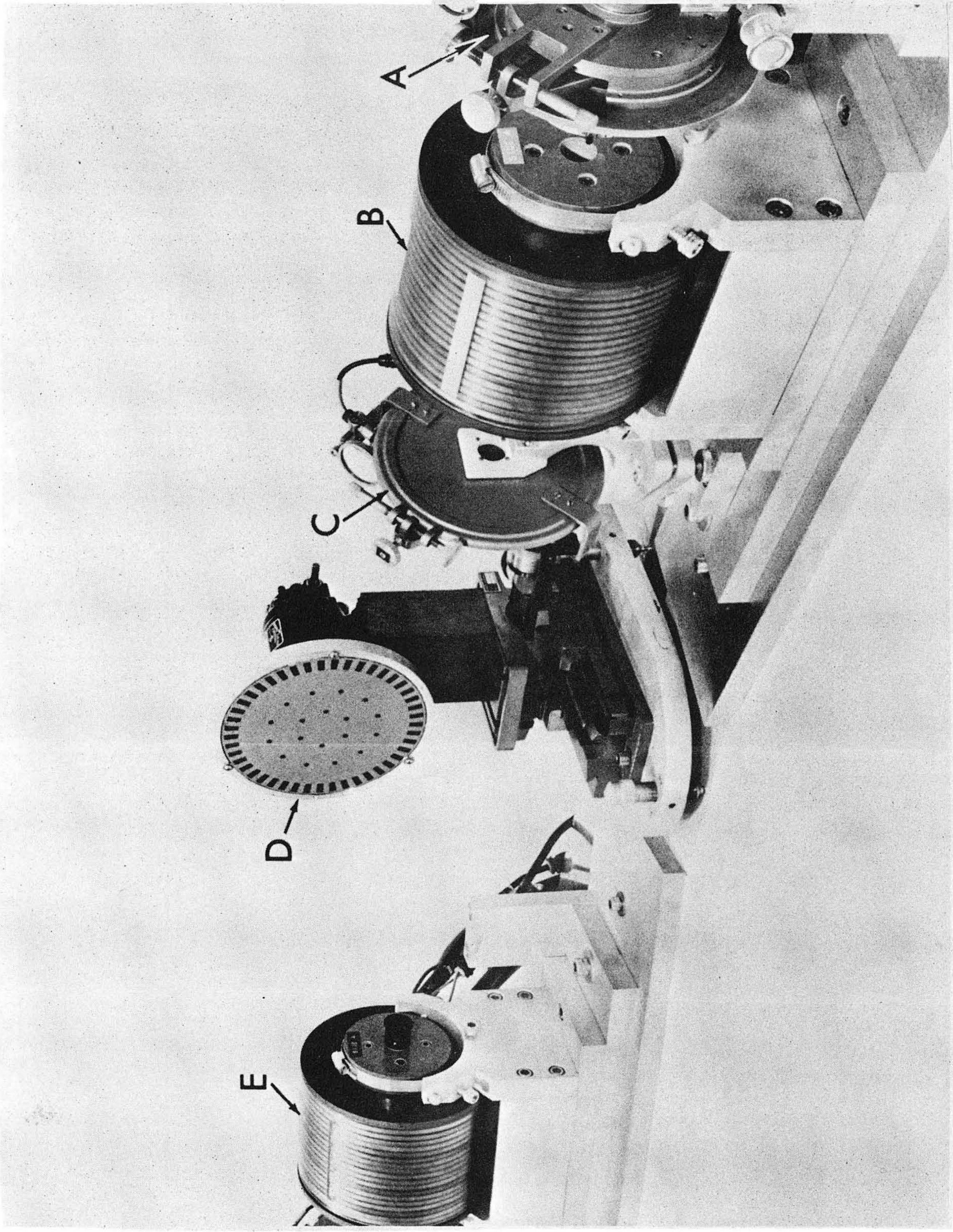
Fig. 9. Dependence of resolution and slew-rate for polarizer and analyzer azimuth on the time-constant of the circuit. Mirror No. 1, 300 rpm and mirror No. 2, 1.3 rpm.

Fig. 10. Slow-mode peak-to-peak amplitude response to sinusoidal variations in analyzer azimuth of different frequency (mirror No. 4).[12] Time-constants: (a) 10^{-3}s, (b) 10^{-2}s, (c) 10^{-1}s, (d) 10^{-1}s.[13]



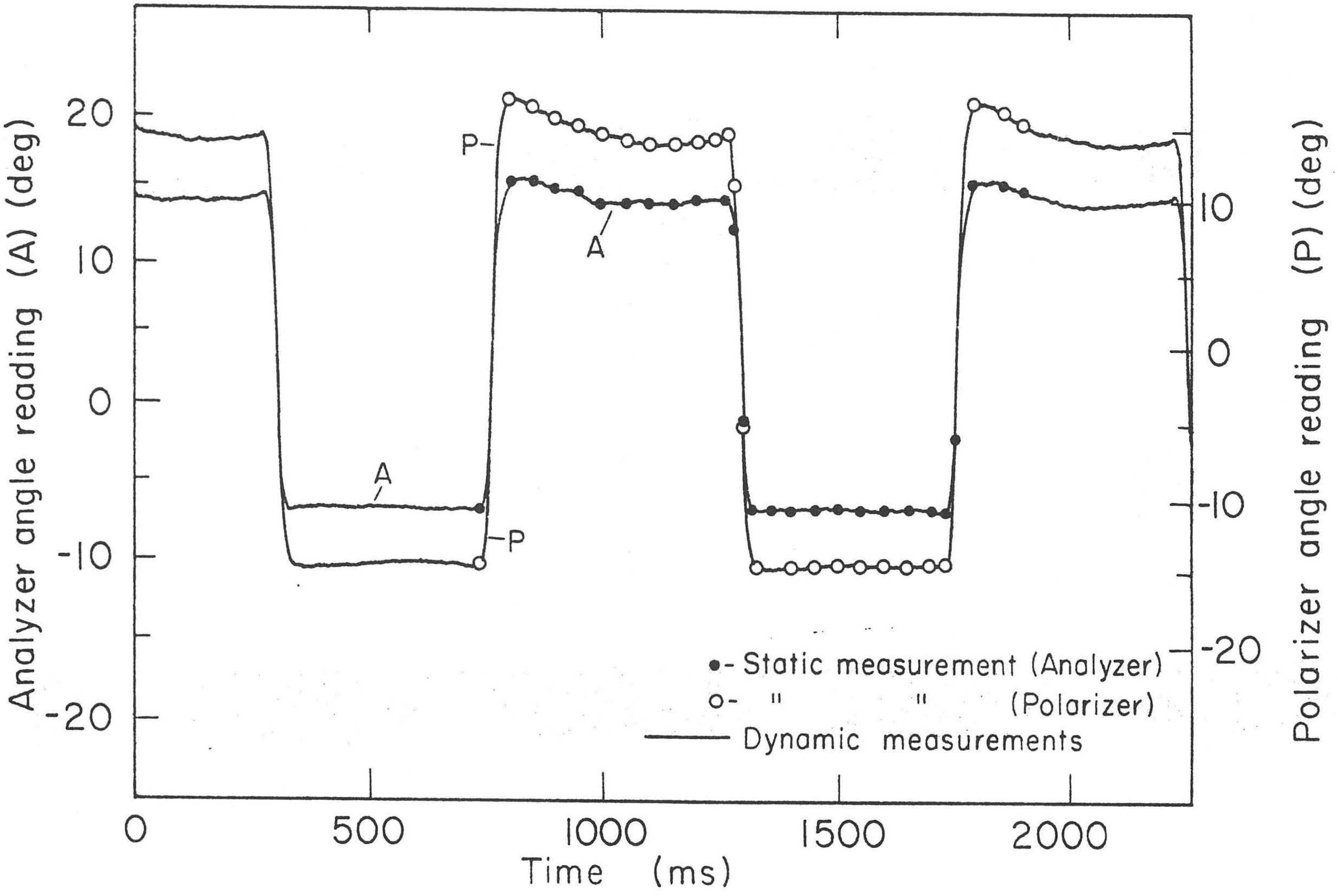
XBL 737-3607

Fig. 1



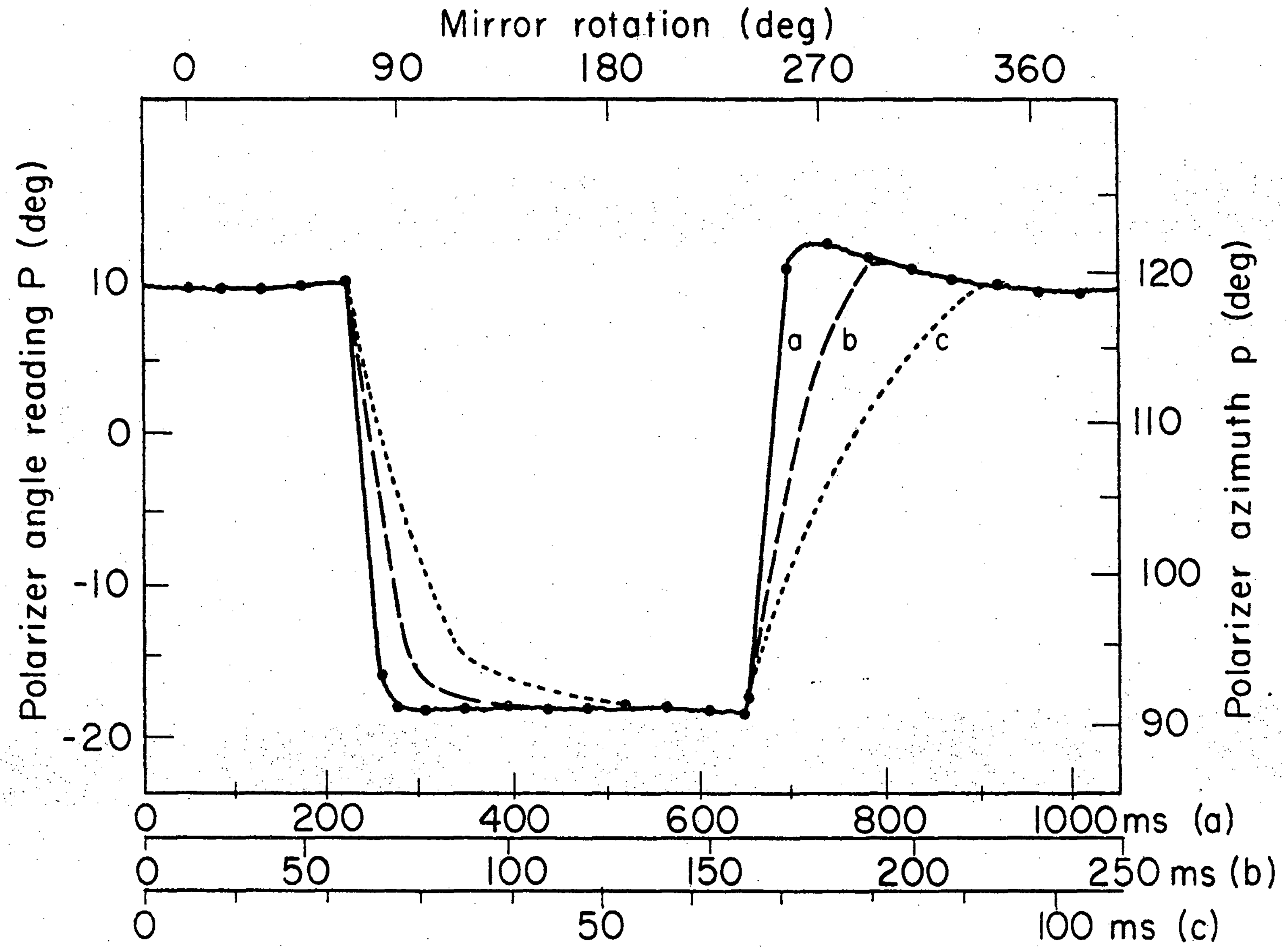
CBB 737-4398

Fig. 2



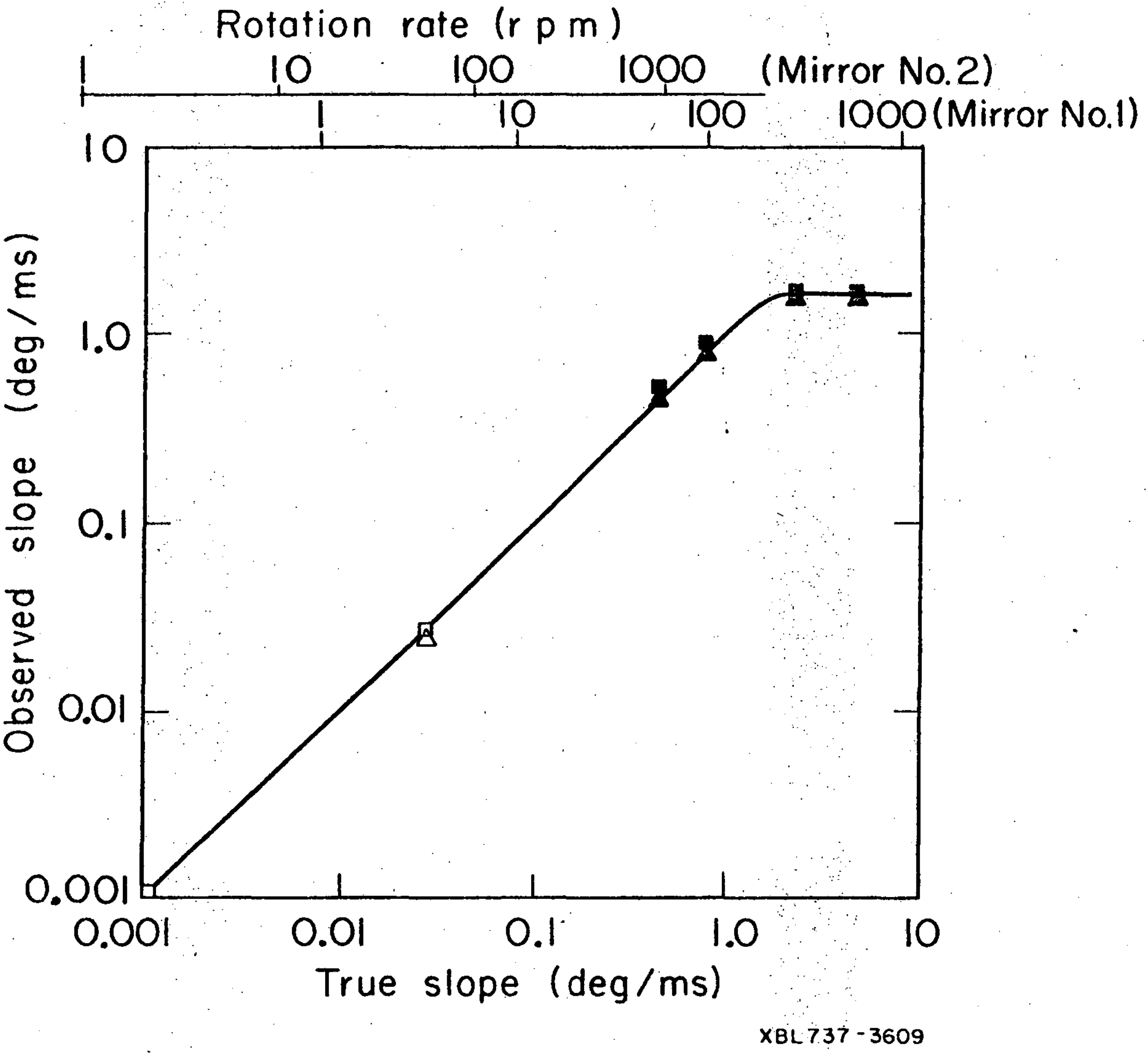
XBL735-2967

Fig. 3



XBL 737-3610

Fig. 4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1
10
100
1000
(Mirror No.2)
1
10
100
1000 (Mirror No.1)
10
1.0
0.1
0.01
0.001
Observed slope (deg/ms)
0.001
0.01
0.1
1.0
10
True slope (deg/ms)
XBL737-3609

Fig. 5

0 0 0 0 3 9 0 / 0 7 4

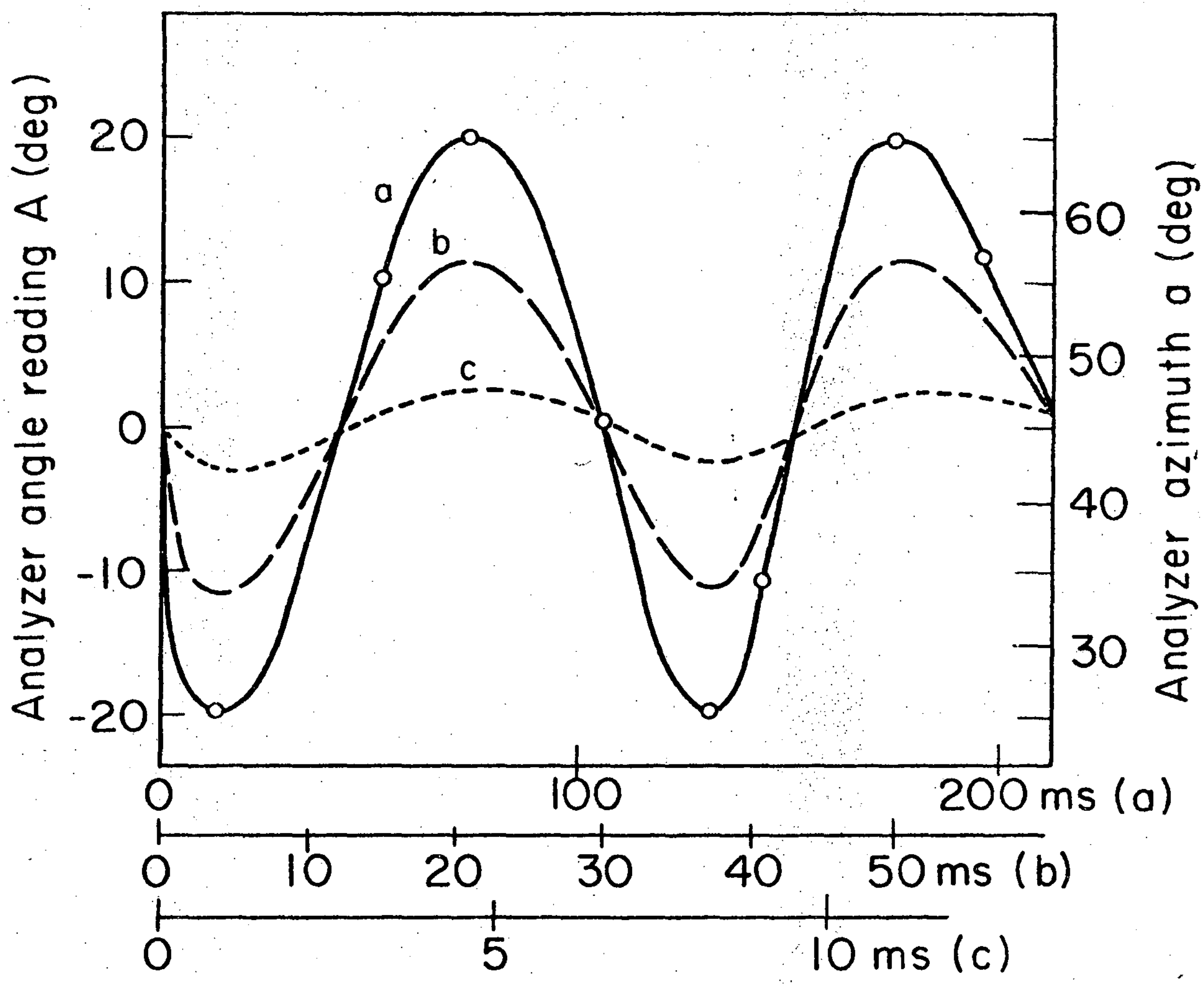

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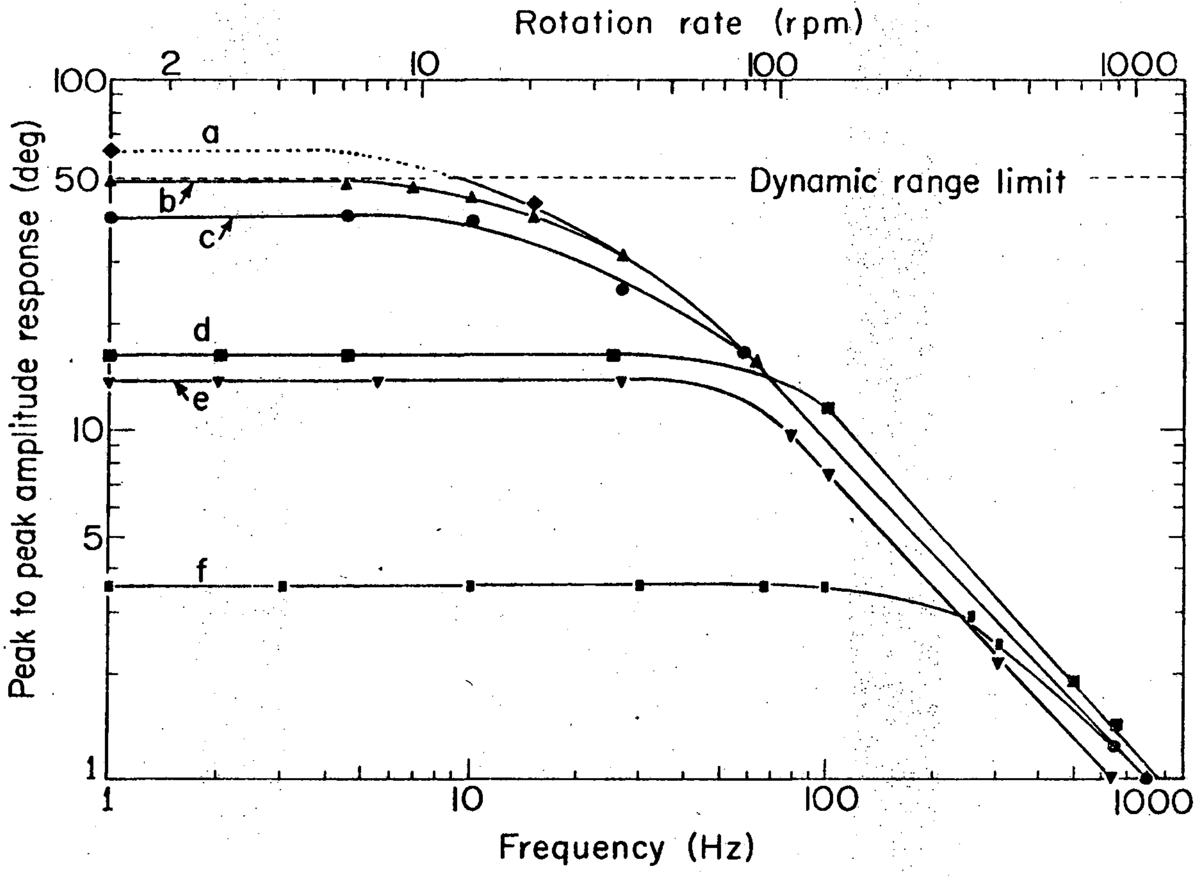
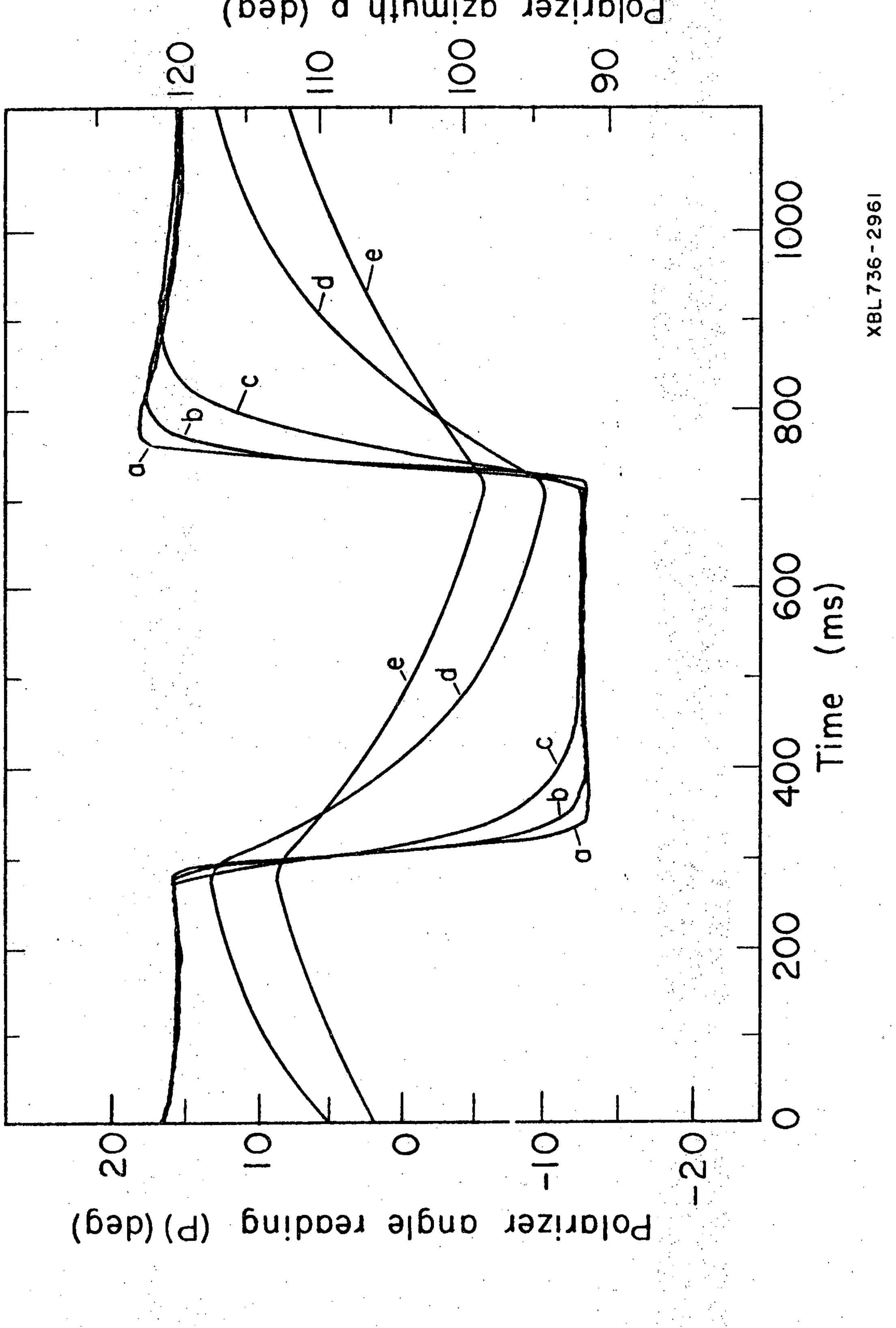
Fig. 6



XBL737-3436

Fig. 7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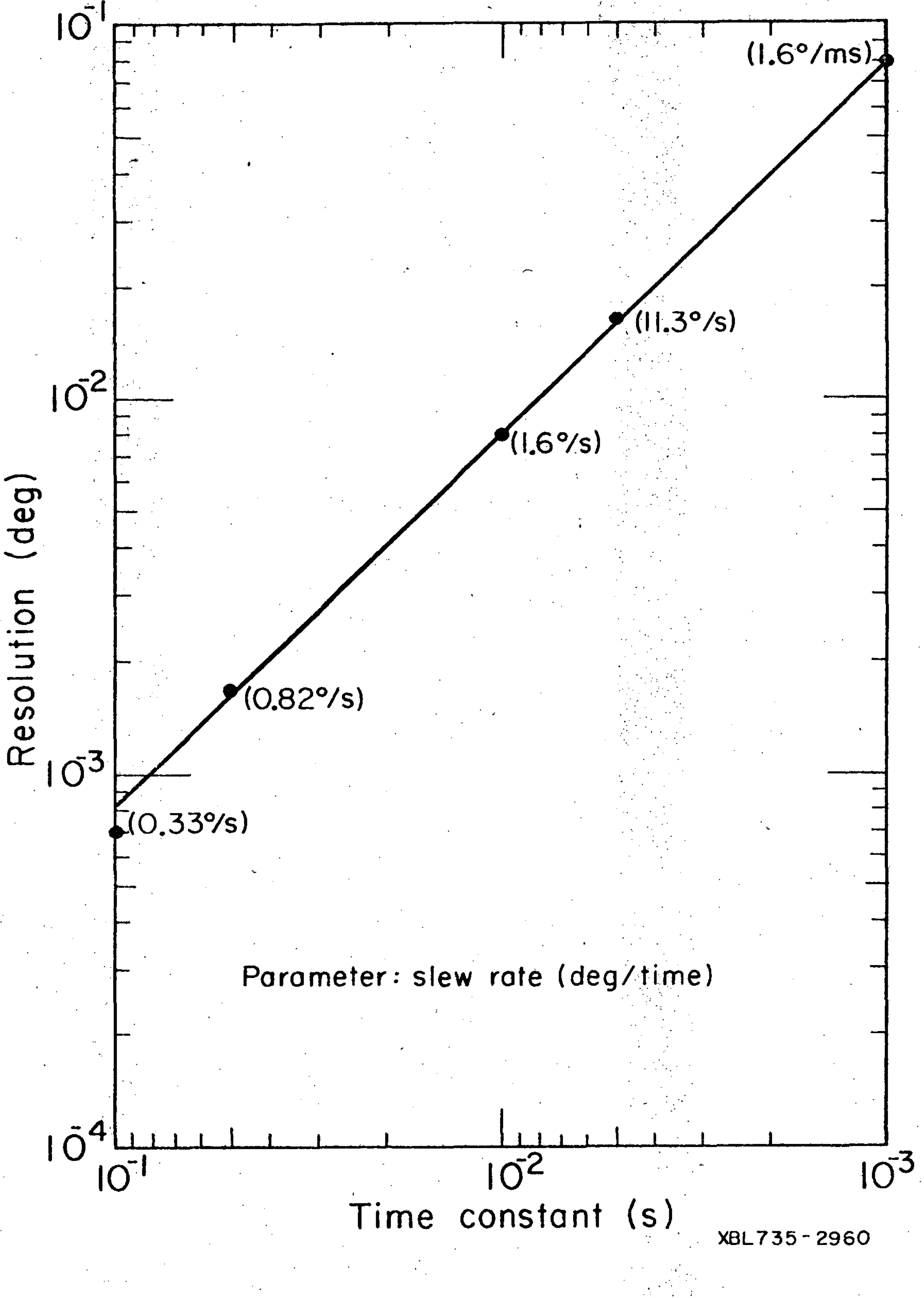
120
110
100
90
Polarizer angle reading (P) (deg)
20
10
0
-10
-20
Time (ms)
0
200
400
600
800
1000
a
b
c
d
e
XBL 736-2961

Fig. 8


Resolution (deg)
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10^{-2}
10^{-3}
10^{-4}
Time constant (s)
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10^{-2}
10^{-3}
(1.6°/ms)
(11.3°/s)
(1.6°/s)
(0.82°/s)
(0.33°/s)
Parameter: slew rate (deg/time)
XBL735-2960

Fig. 9

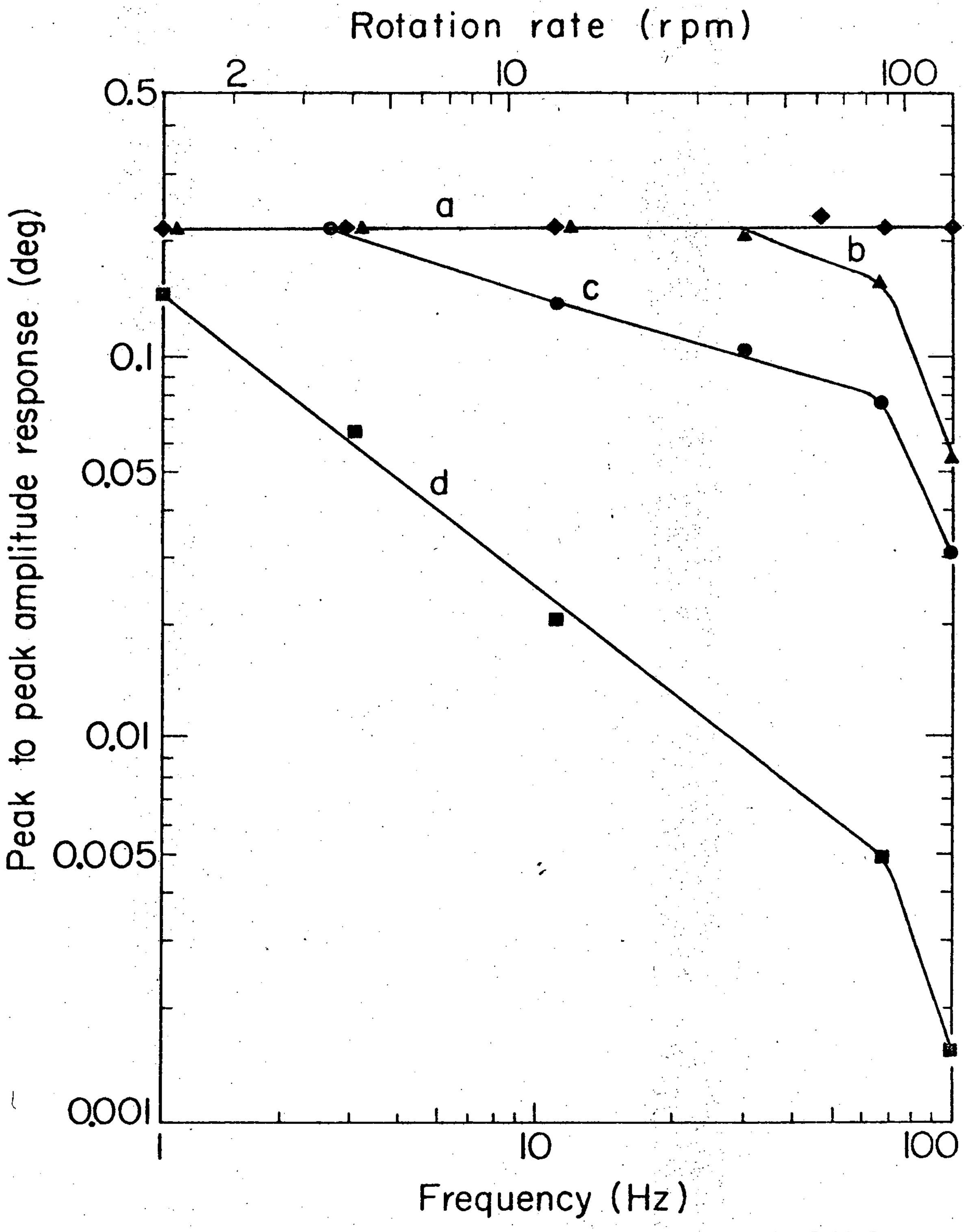

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Fig. 10

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