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SIMULATION OF SHIP YAWING

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SIMULATION OF SHIP YAWING

Claes Källström

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TABLE OF CONTENTS

1. INTRODUCTION

Simulations of manoeuvring trials and simulations of yaws performed by a yaw regulator are presented in this report. The simulations are performed on the computer UNIVAC 1108 by use of the interactive program SIMNON (see Elmqvist (1975)). The ship model used describes a 350 000 tdw tanker of Kockums' design.

The yaw regulator consists of different discrete, fixed gain PID-regulators. The reference values used by the yaw regulator are the yaw rate and the heading angle. Full-scale experiments on 255 000 tdw tankers with modified yaw regulators are described in Källström (1974) and (1975) where also straight course keeping experiments are presented.

Simulations of straight course keeping by different autopilots are discussed in Aspernäs and Foisack (1975), Aspernäs and Källström (1975) and Källström (1976).

Listings of the program used are given in the Appendix.

2. SHIP STEERING DYNAMICS

The following model, which describes a 350 000 tdw tanker of Kockums design, is used in the simulations (cf. Norrbin (1970)):

$$\dot{\delta} = -\frac{1}{T_r}\,\delta + \frac{1}{T_r\cdot CRG}\,\delta_c$$

$$|\dot{\delta}| \leq \frac{1}{CRG}\,\delta_{lim}$$

$$\begin{aligned}\left(1 - X''_{\dot{u}}\right)\dot{u} = {} & \frac{1}{L}X''_{u|u|}\,u|u| + \frac{1}{L}X''_{uu}\,u^2 + \left(1 + X''_{vr}\right)vr + \\ & + L\left(X''_{rr} + x''_G\right)r^2 + \frac{1}{gL^2}X''_{uvv|v|}\,uv^2|v| + \frac{1}{L}X''_{u|u|\delta\delta}\,u|u|\delta^2 + \\ & + (1-t)\;(T/m) - F_w\cos\left(\frac{\alpha}{CRG} - \psi\right)\end{aligned}$$

$$\begin{aligned}\left(1 - Y''_{\dot{v}}\right)\dot{v} = {} & \left(Y''_{ru} - 1\right)ru + \frac{1}{\sqrt{gL}}Y''_{ru|u|}\,ru|u| + \\ & + \frac{1}{L}Y''_{|u|v}\,|u|v + \frac{1}{\sqrt{gL^3}}Y''_{u|u|v}\,u|u|v + \frac{1}{L}Y''_{v|v|}\,v|v| + \\ & + Y''_{r|v|}\,r|v| + Y''_{|r|v}\,|r|v + \frac{1}{L}Y''_{uu\delta}\,u^2\delta + \frac{1}{L}Y''_{u|u|\delta}\,u|u|\delta + \\ & + Y''_{T\delta}\;(T/m)\;\delta + k_{TY}\;(T/m) - F_w\sin\left(\frac{\alpha}{CRG} - \psi\right) + w_1\end{aligned}$$

$$\begin{aligned}\left(k''^2_{zz} - N''_{\dot{r}}\right)\dot{r} = {} & \frac{1}{L}\left(N''_{r|u|} - x''_G\right)r|u| + \frac{1}{\sqrt{gL^3}}N''_{ru|u|}\,ru|u| + \\ & + \frac{1}{L^2}N''_{uv}\,uv + \frac{1}{\sqrt{gL^5}}N''_{u|u|v}\,u|u|v + \frac{1}{L^2}N''_{v|v|}\,v|v| + N''_{r|r|}\,r|r| + \\ & + \frac{1}{L}N''_{r|v|}\,r|v| + \frac{1}{L}N''_{|r|v}\,|r|v + \frac{1}{L^2}N''_{uu\delta}\,u^2\delta + \frac{1}{L^2}N''_{u|u|\delta}\,u|u|\delta + \\ & + \frac{1}{L}N''_{T\delta}\,(T/m)\;\delta + \frac{1}{L}k_{TN}\,(T/m) + \frac{1}{L^2}F_w\,\ell_w\sin\left(\frac{\alpha}{CRG} - \psi\right) + w_2\end{aligned}$$

$$\dot{\psi} = r$$

$$\dot{x}_o = u \cos \psi - v \sin \psi$$

$$\dot{y}_o = u \sin \psi + v \cos \psi \qquad (2.1)$$

It is assumed that the number of propeller revolutions n is kept constant to the value 87.6 rpm by a regulator during all the simulations. The propeller thrust per mass unit (T/m) is computed by:

$$J = \frac{u(1-w)\cdot 60}{n\,D}$$

$$J' = \frac{J}{\sqrt{1+J^2}}$$

$$K_T' = -0.33\cdot J'^2 - 0.38\cdot J' + 0.35 \qquad (2.2)$$

$$T = K_T' \left(\frac{J}{J'}\right)^2 \rho_s\, n^2\, D^4 / 3600$$

$$(T/m) = \frac{T}{\rho_s\, \nabla}$$

Notice that the terms $(T/m)\delta$ in (2.1) always are limited by the value $(T/m)_0\delta$, where $(T/m)_0$ is computed from (2.2) with the stationary forward speed corresponding to n = 87.6 rpm.

Input signal:

rudder command (or rudder servo position)	δ_c	[deg]

States:

rudder angle	δ	[rad]
forward velocity	u	[m/s]
sway velocity	v	[m/s]

yaw rate	r [rad/s]
heading angle	ψ [rad]
x-coordinate (system fixed earth)	x_o [m]
y-coordinate (system fixed earth)	y_o [m]

Disturbances:

sway acceleration disturbance	w_1 [m/s^2]
disturbance of yaw angle acceleration	w_2 [rad/s^2]

Other notations:

time constant of rudder servo	T_r [s]
limit of rudder rate	δ_{lim} [deg/s]
length of ship	L [m]
acceleration of gravity	g [m/s^2]
propeller thrust per mass unit	T/m [m/s^2]
number of propeller revolutions	n [rpm]
wind force per mass unit	F_w [m/s^2]
lever arm of wind force	ℓ_w [m]
angle of wind direction	α [deg]
conversion factor rad - deg	CRG [deg]

The following parameter values are used:

T_r = 5 s
δ_{lim} = 2.32 deg/s
L = 350 m
g = 9.80665 m/s^2
n = 87.6 rpm
ℓ_w = 25 m
CRG = 57.2958 deg

The values of the other parameters are given in Dyne and Trägårdh (1975). Two different load conditions are considered corresponding to the mean draught $T = 22.3$ m (full load, forward and aft draught equal to 22.3 m) and $T = 10.5$ m (ballast, forward and aft draught equal to

9.0 m and 12.0 m, resp.). The forward speed u which corresponds to $n = 87.6$ rpm is equal to 15.8 knots when $T = 22.3$ m and equal to 17.25 knots when $T = 10.5$ m. These two values of the forward speed u are used as initial values in all the simulations. If the model (2.1) and (2.2) is linearized, the following transfer function relating the yaw rate r to the rudder angle δ is obtained:

$$G(s) = \frac{K\ (1+sT_3)}{(1+sT_1)\ (1+sT_2)} \qquad (2.3)$$

If the forward speed u is assumed to be constant and equal to 15.8 knots, then the following parameter values of (2.3) are obtained when $T = 22.3$ m:

$$\begin{aligned} K &= 0.0161 \ \text{1/s} \\ T_1 &= -110.1 \ \text{s} \\ T_2 &= 18.3 \ \text{s} \\ T_3 &= 54.3 \ \text{s} \end{aligned} \qquad (2.4)$$

The corresponding values when $u = 17.25$ knots and $T = 10.5$ m are:

$$\begin{aligned} K &= 0.0707 \ \text{1/s} \\ T_1 &= -337.1 \ \text{s} \\ T_2 &= 19.9 \ \text{s} \\ T_3 &= 69.5 \ \text{s} \end{aligned} \qquad (2.5)$$

Notice that the sign of the rudder angle in the model is chosen in such a way that a positive rudder angle (port rudder) gives a negative yaw rate (port yaw). From (2.4) and (2.5) it can be concluded that the tanker is unstable in full load condition as well as in ballast condition.

The disturbance signals w_1 and w_2 are obtained as white, gaussian noise filtered through a low pass filter. The covariance matrix of the white noise vector, which generates w_1 and w_2, is

$$R_w = \begin{bmatrix} 10^{-10} & 0 \\ 0 & 10^{-12} \end{bmatrix} \tag{2.6}$$

The measured outputs from the model (2.1) and (2.2) are

$$r_m = \bar{r} + e_1, \qquad \bar{r} = CRG \cdot r$$

$$\psi_m = \bar{\psi} + e_2, \qquad \bar{\psi} = CRG \cdot \psi$$

where e_1 and e_2 are white, gaussian measurement noise with covariance matrix

$$R_e = \begin{bmatrix} \sigma_r^2 & 0 \\ 0 & 0.01 \end{bmatrix} \tag{2.7}$$

where $\sigma_r = 0.01$ or 0.02 deg/s.

The measured yaw rate r_m [deg/s] and the measured heading ψ_m [deg] are used by the yaw regulator.

Three different cases of disturbances are used in the simulations:

1. No disturbances: $F_w = 0$, $w_1 = w_2 = e_1 = e_2 = 0$.
2. Constant wind force disturbance: $F_w = 0.002$ m/s^2,
   $w_1 = w_2 = e_1 = e_2 = 0$.
3. Stochastic disturbances: $F_w = 0.002$ m/s^2, R_w and R_e
   according to (2.6) and (2.7), resp.

It should be pointed out that the model of the disturbances is extremely simplified. A more realistic approach is given in Berlekom, Trägårdh and Dellhag (1975).

The program of the ship model, TANK1, is given in the Appendix.

3. YAW REGULATOR

A yaw performed by the yaw regulator consists of four different phases, viz. the initial phase (phase 1), the phase of constant yaw rate (phase 2), the checking rudder phase (phase 3) and the terminating phase (phase 4). However, if the requested heading change $\Delta\psi_{ref}$ is small, one or more of the phases may be skipped. The measurement signals used by the yaw regulator are the yaw rate r_m and the heading ψ_m, and the reference values used are the requested yaw rate r_{ref} and the new requested heading ψ_{ref}.

Modified discrete, fixed gain PID-regulators are used in the different phases (note that $n = 0,1,2,\ldots$):

Phase 1:

$$\delta_c(nT_s) = k_4 [r_m(nT_s) - r_{ref}] + \bar{\delta}_c$$

$$\left| k_4 [r_m (nT_s) - r_{ref}] \right| \leq \left| c_1 r_{ref} \right|$$

Phase 2:

$$\delta_c(nT_s) = k_5 [r_m(nT_s) - r_{ref}] + k_6 T_s \sum_{i=0}^{n} [r_m(iT_s) - r_{ref}] + \bar{\delta}_c$$

Phase 3:

$$\delta_c(nT_s) = k_7 [\psi_m(nT_s) - \psi_{ref}] + k_8 r_m(nT_s)$$

$$\left| \delta_c(nT_s) \right| \leq \left| c_3 r_{ref} \right|$$

Phase 4:

$$\delta_c(nT_s) = k_1 [\psi_m(nT_s) - \psi_{ref}] + k_2 r_m(nT_s) +$$

$$+ k_3 T_s \sum_{i=0}^{n} [\psi_m(iT_s) - \psi_{ref}]$$

The sampling interval T_s is always equal to 10 s. The moving average $\bar{\delta}_c$ of the rudder commands δ_c is only updated during phase 4:

$$\bar{\delta}_c\Big((k+1)\ T_s\Big) = \bar{\delta}_c(kT_s) + \left(\frac{1-\gamma}{k+1} + \gamma\right)\Big(\delta_c(kT_s) - \bar{\delta}_c(kT_s)\Big),$$

$k = 0,\ 1,\ 2,\ \ldots$

$\bar{\delta}_c(0) = 0$

The computation of $\bar{\delta}_c$ is initialized every time phase 4 is entered. The value of γ is always equal to 0.05.

The conditions to jump from one phase to another read (notice that phase 4 also is used for straight course keeping):

Phase 4 → phase 1:

$\Delta\psi_{ref} > \psi_{max}$

Phase 1 → phase 2:

$r_{ref} > 0$ and $r_m - r_{ref} > -\varepsilon_1$
or
$r_{ref} < 0$ and $r_m - r_{ref} < \varepsilon_1$
or
(time in phase 1) $> T_1$

Phase 1 or 2 → 3:

$\psi_m - \psi_{ref} < 0$ and $-c_2\ r_m < \psi_m - \psi_{ref}$
or
$\psi_m - \psi_{ref} > 0$ and $-c_2\ r_m > \psi_m - \psi_{ref}$

Phase 3 → 4:

$|r_m| < \varepsilon_2$
or
$r_{ref} > 0$ and $\psi_m - \psi_{ref} > -\varepsilon_3$
or
$r_{ref} < 0$ and $\psi_m - \psi_{ref} < \varepsilon_3$
or
(time in phase 3) $> T_3$

Two sets of yaw regulator parameters are used. The first set contains rather large gain factors:

$k_1 = 5$
$k_2 = 200$ s
$k_3 = 0.005$ 1/s
$k_4 = 200$ s
$k_5 = 200$ s
$k_6 = 8$
$k_7 = 2$
$k_8 = 200$ s

$\varepsilon_1 = 0$ deg/s
$\varepsilon_2 = 0.02$ deg/s
$\varepsilon_3 = 1$ deg
$c_1 = 60$ s
$c_2 = 50$ s
$c_3 = 60$ s
$T_1 = 30$ s
$T_3 = 80$ s
$\psi_{max} = 2.5$ deg

The values of the parameters k_1-k_8 are decreased in the second set:

$k_1 = 2.5$
$k_2 = 100$ s
$k_3 = 0.0025$ 1/s
$k_4 = 100$ s

$k_5 = 100$ s
$k_6 = 4$
$k_7 = 1$
$k_8 = 100$ s

The program of the yaw regulator, YAW1, is given in the Appendix. A special indicator M_y is used to describe the actual yaw phase, i.e. $M_y = 1,2,3$ corresponds to phase 1,2,3, resp. Notice, however, that phase 4 is indicated by $M_y = 0$.

4. SIMULATION OF MANOEUVRING TRIALS

Simulations of turning circle manoeuvres, spiral tests and zig-zag tests are presented in this chapter. No disturbances are applied, i.e.

$$F_w = 0, \quad w_1 = w_2 = e_1 = e_2 = 0.$$

Plots of the simulations are shown in Figs 4.1 - 4.8. The total speed

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

and the angle of drift

$$\beta = - \text{arctg } (v/u)$$

are shown in some of the figures. The plots may be compared to the simulations in SSPA (1974), where almost the same ship model as in this report was used.

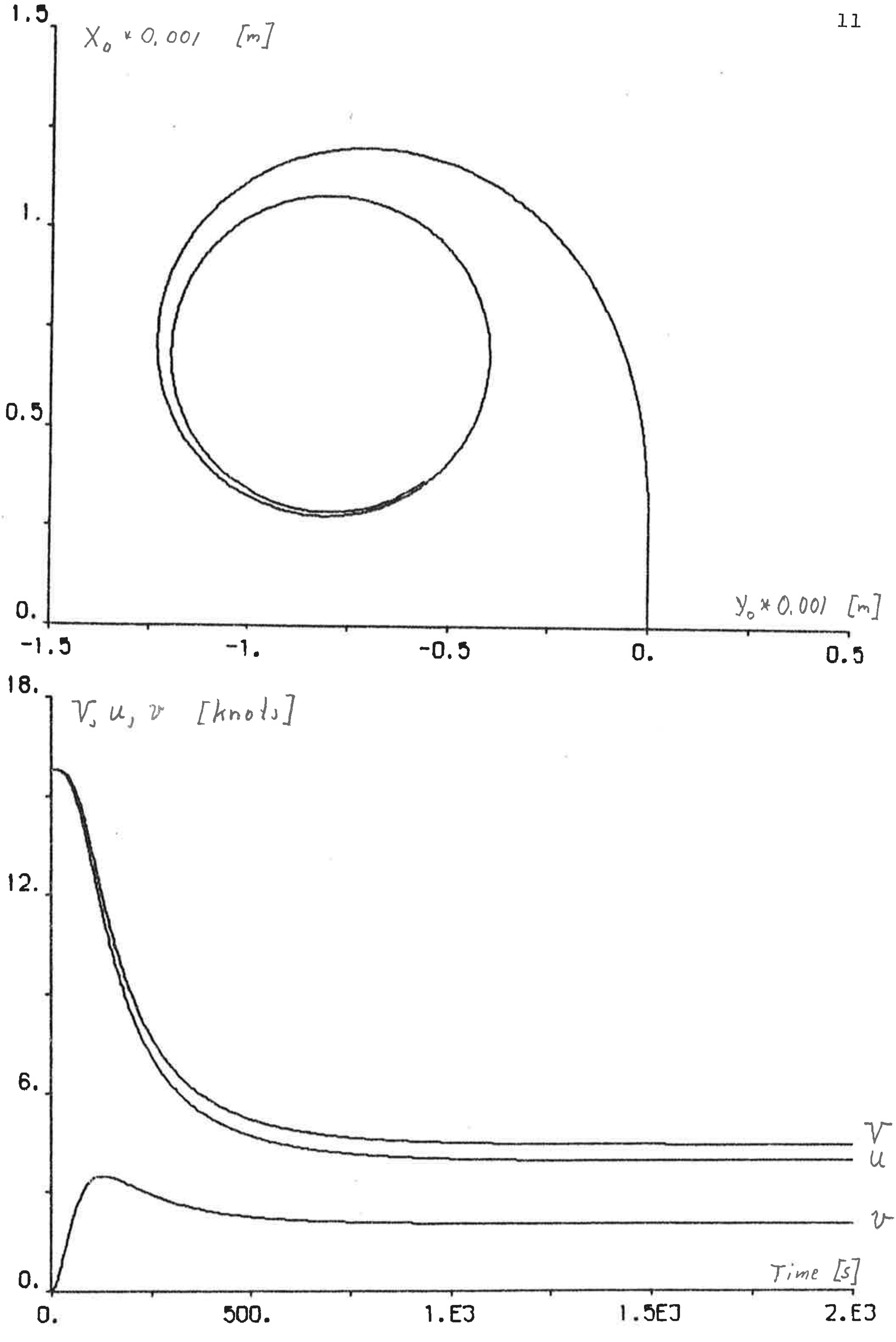


Fig. 4.1 a - Turning circle manoeuvre: T = 22.3 m, δ_c = 35 deg.

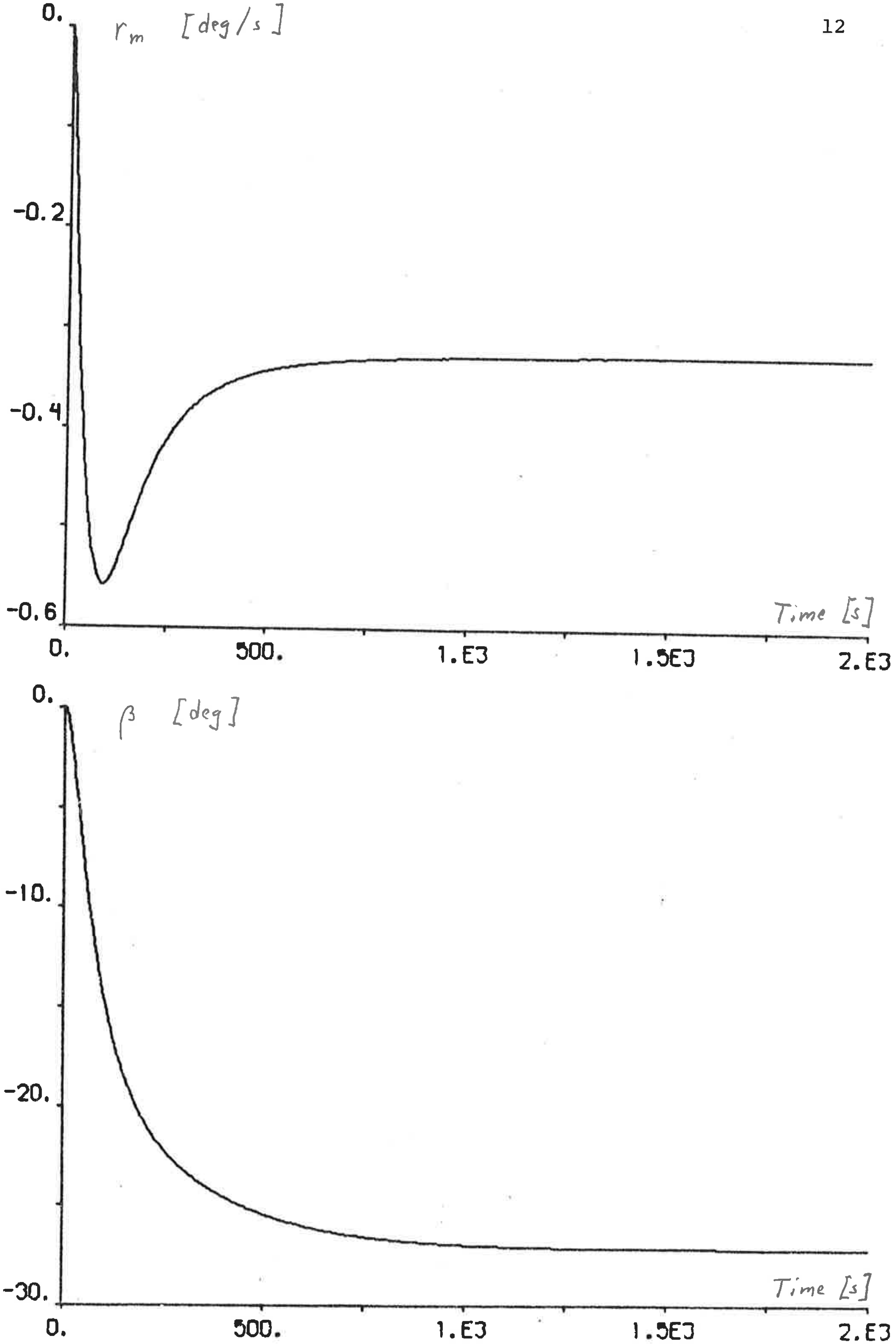

0.
r_m [deg/s]
-0.2
-0.4
-0.6
Time [s]
0.
500.
1.E3
1.5E3
2.E3
0.
β [deg]
-10.
-20.
-30.
Time [s]
0.
500.
1.E3
1.5E3
2.E3

Fig. 4.1 b

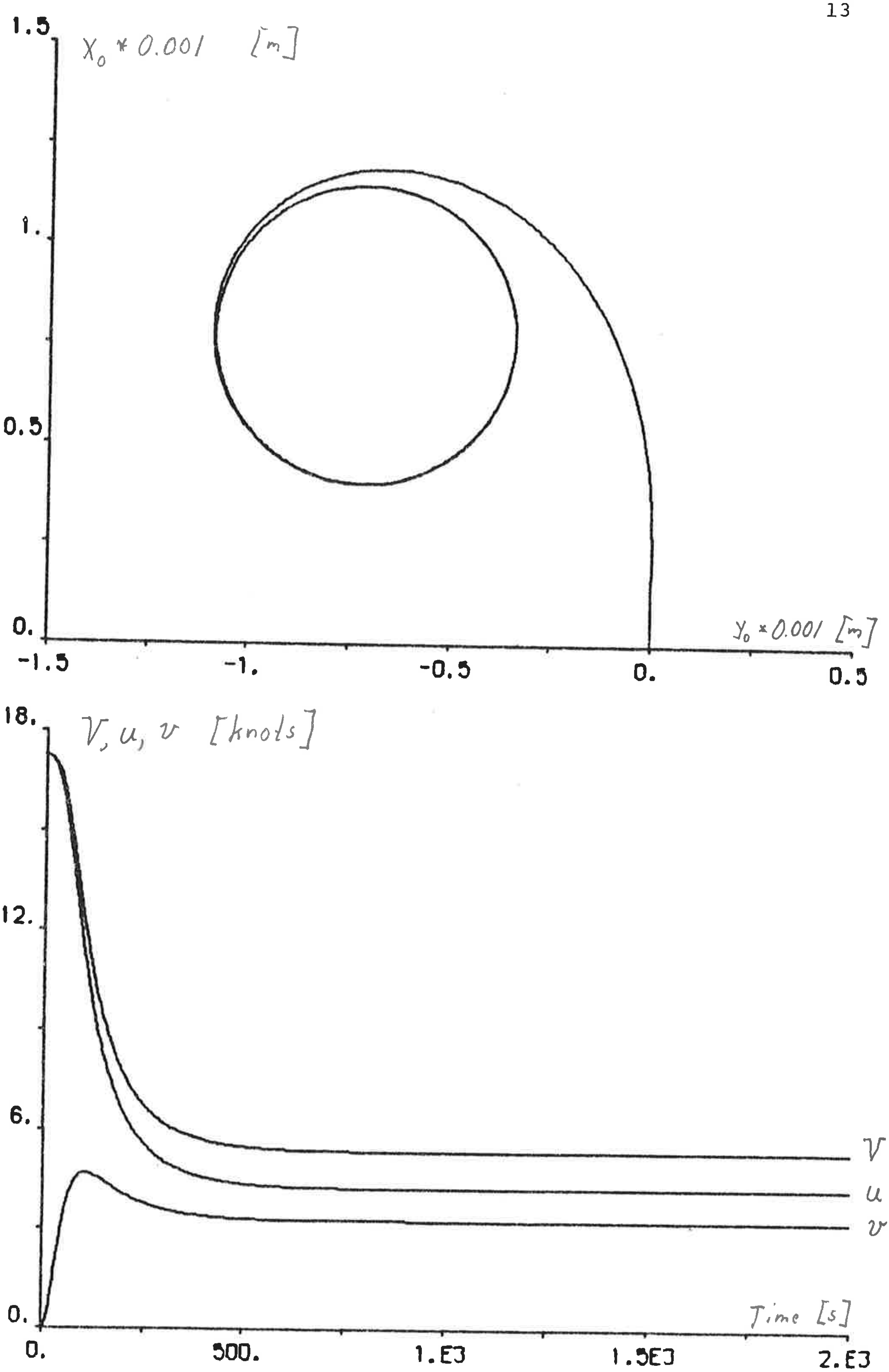
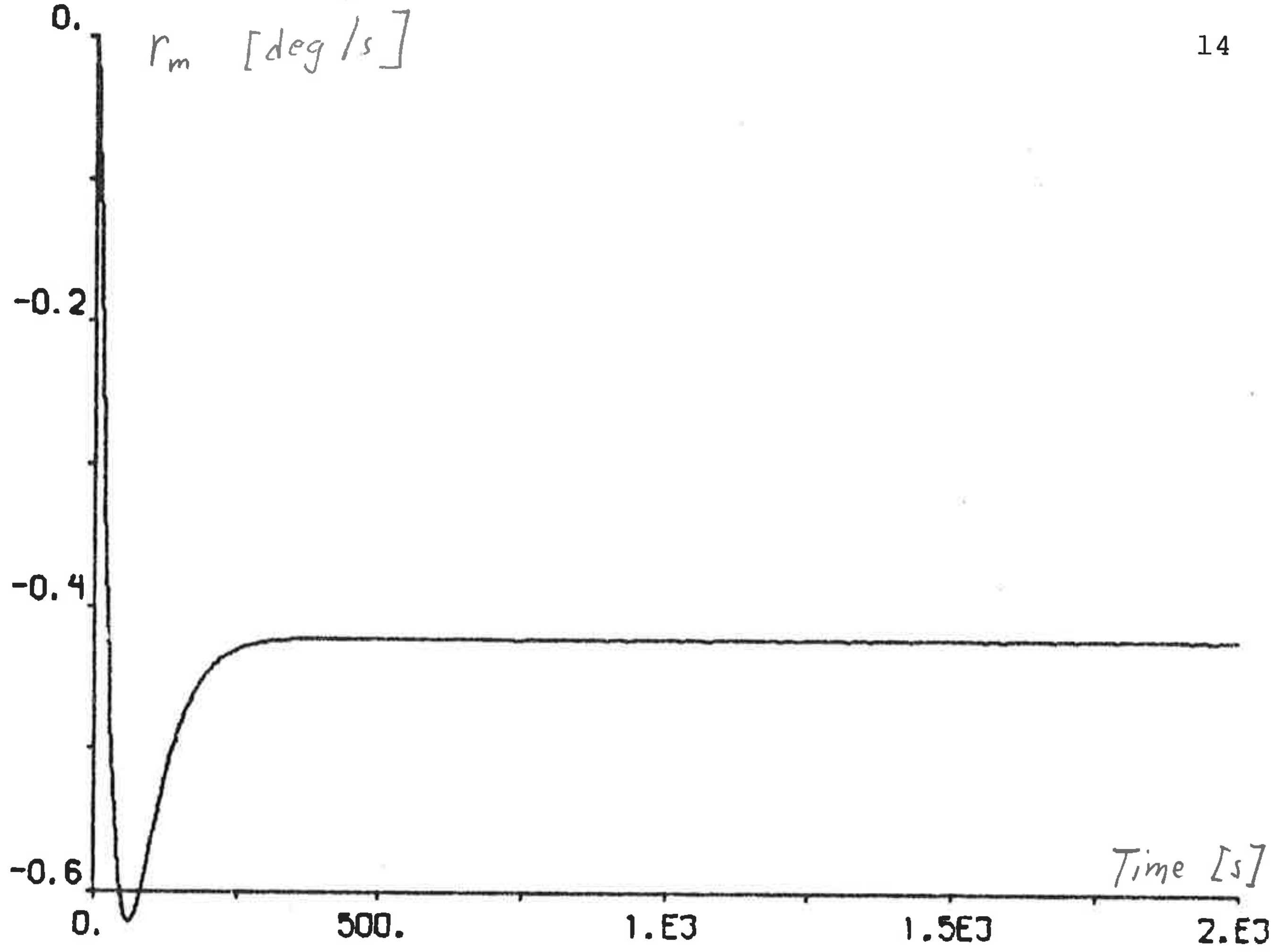


Fig. 4.2 a - Turning circle manoeuvre: T = 10.5 m, δ_c = 35 deg.


0.
r_m [deg/s]
-0.2
-0.4
-0.6
Time [s]
0.
500.
1.E3
1.5E3
2.E3

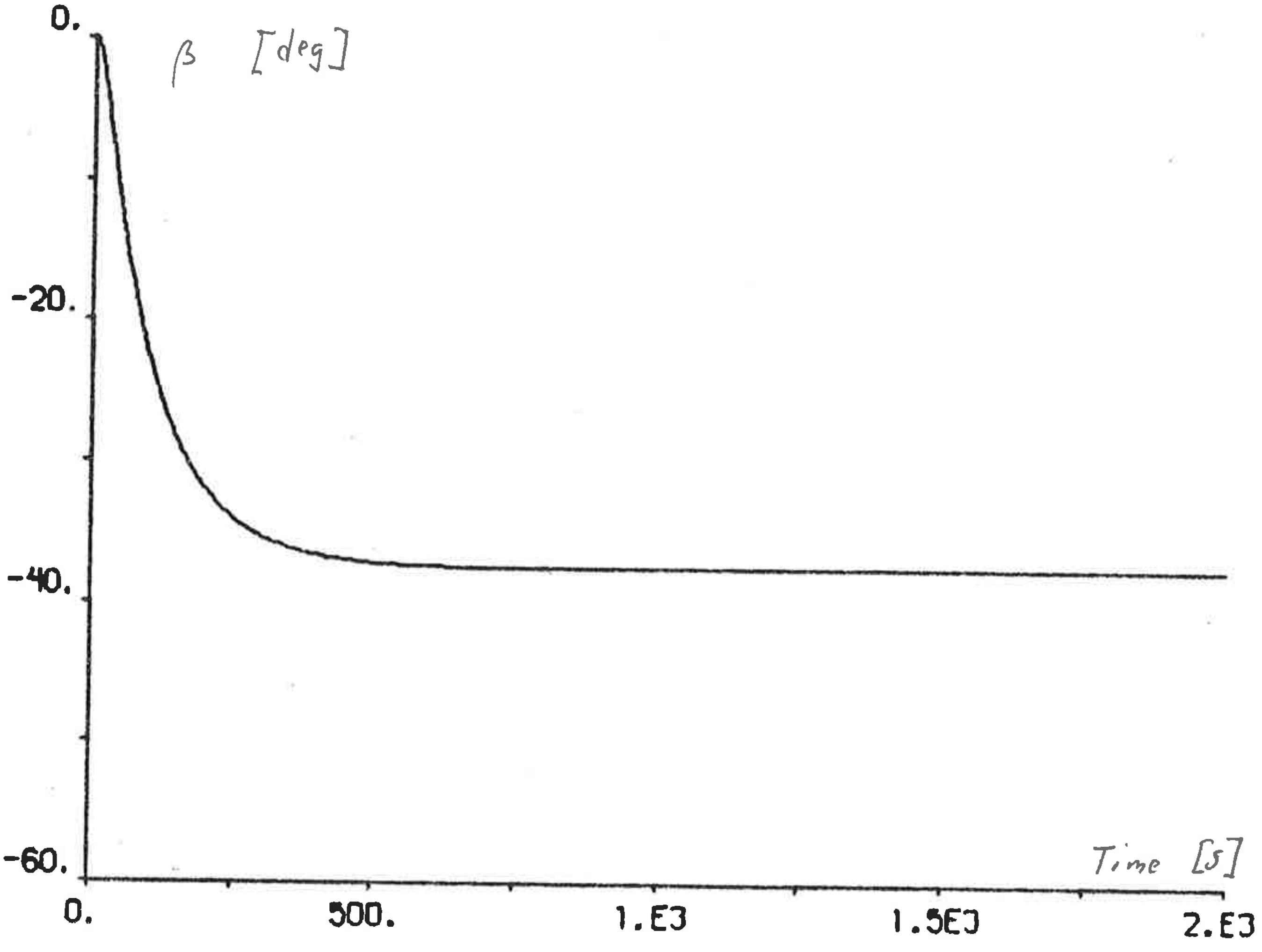

0.
β [deg]
-20.
-40.
-60.
Time [s]
0.
500.
1.E3
1.5E3
2.E3

Fig. 4.2 b

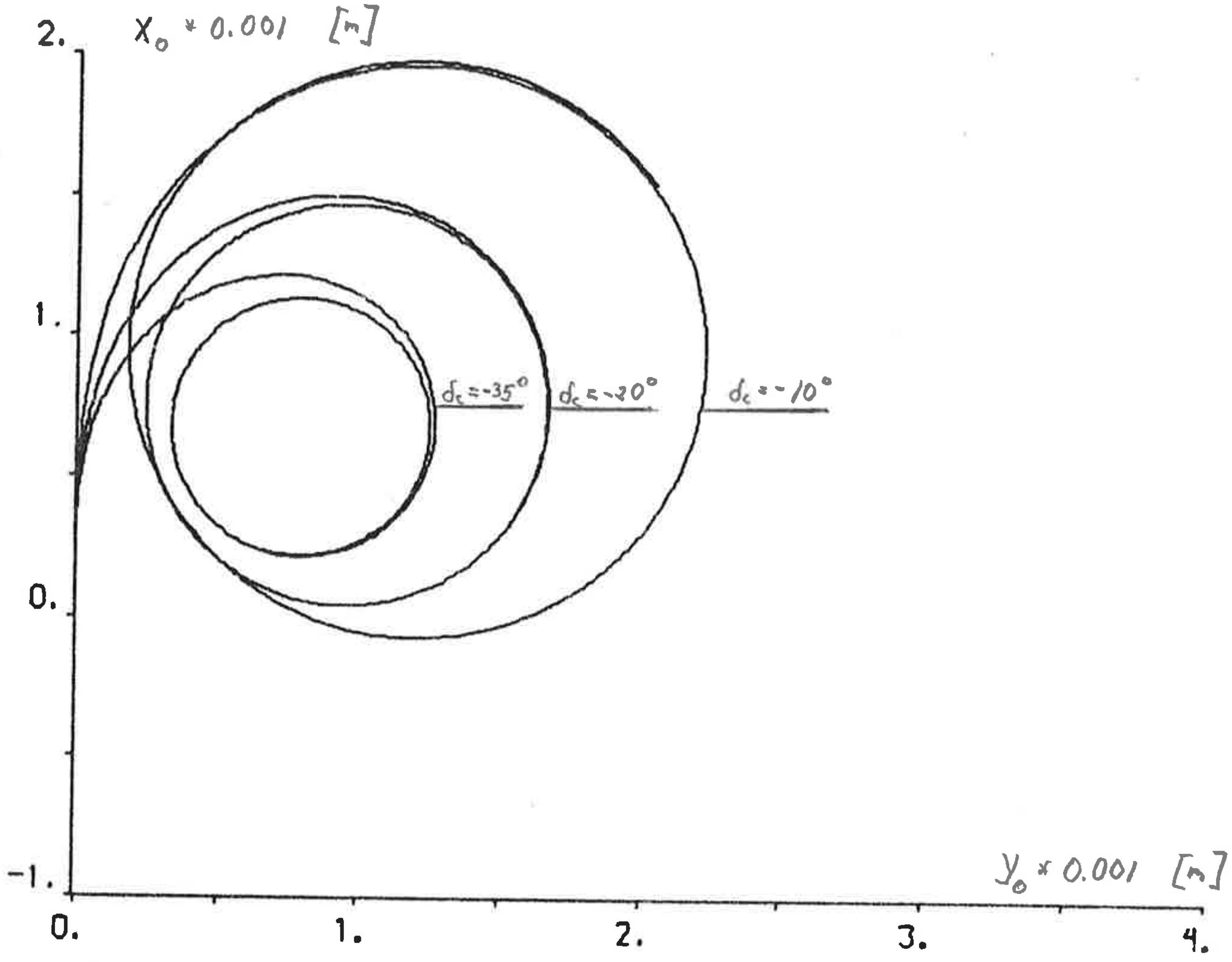


Fig. 4.3 - Turning circle manoeuvres: T = 22.3 m, δ_c = -35, -20, -10 deg.

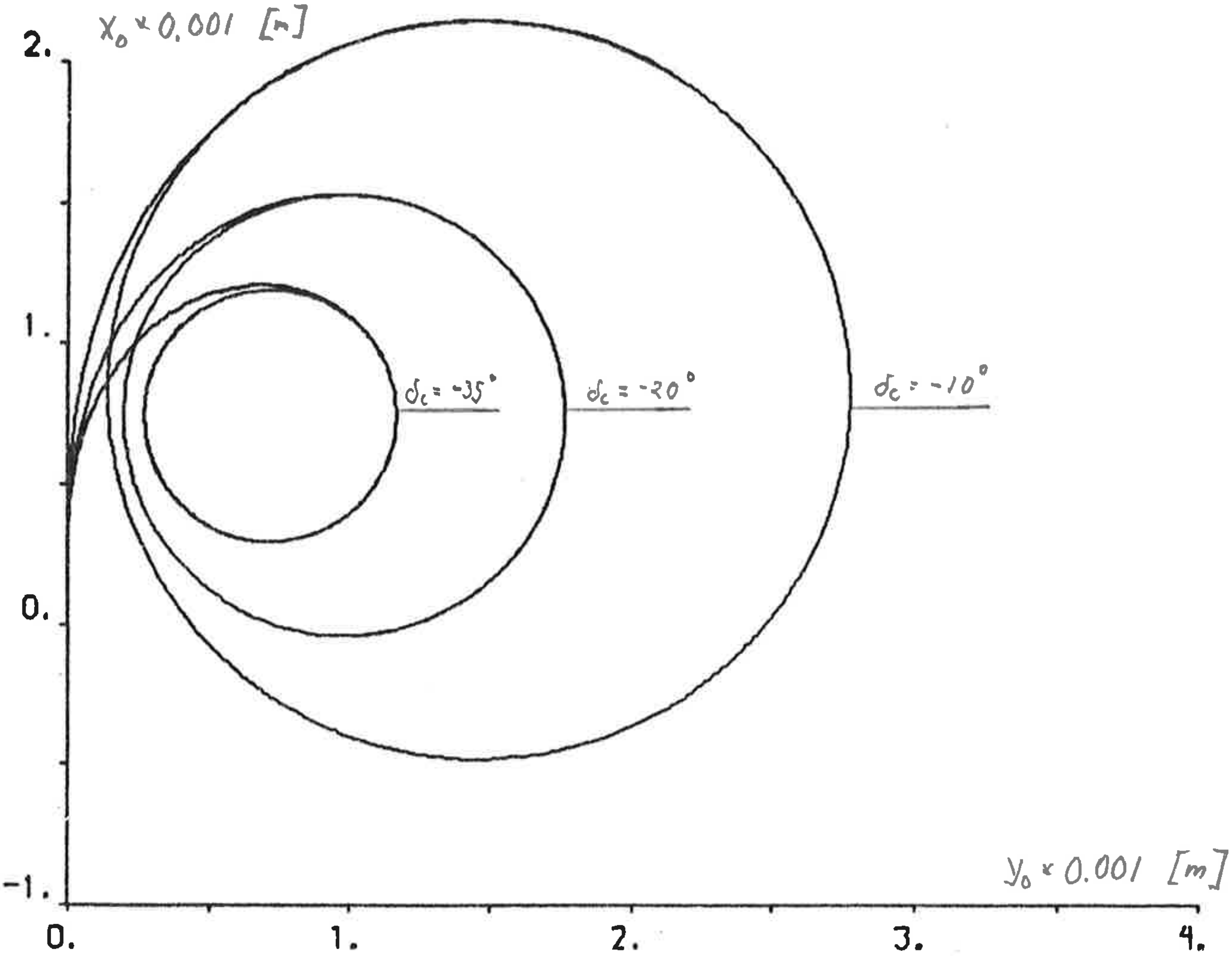


Fig. 4.4 - Turning circle manoeuvres: T = 10.5 m, δ_c = -35, -20, -10 deg.

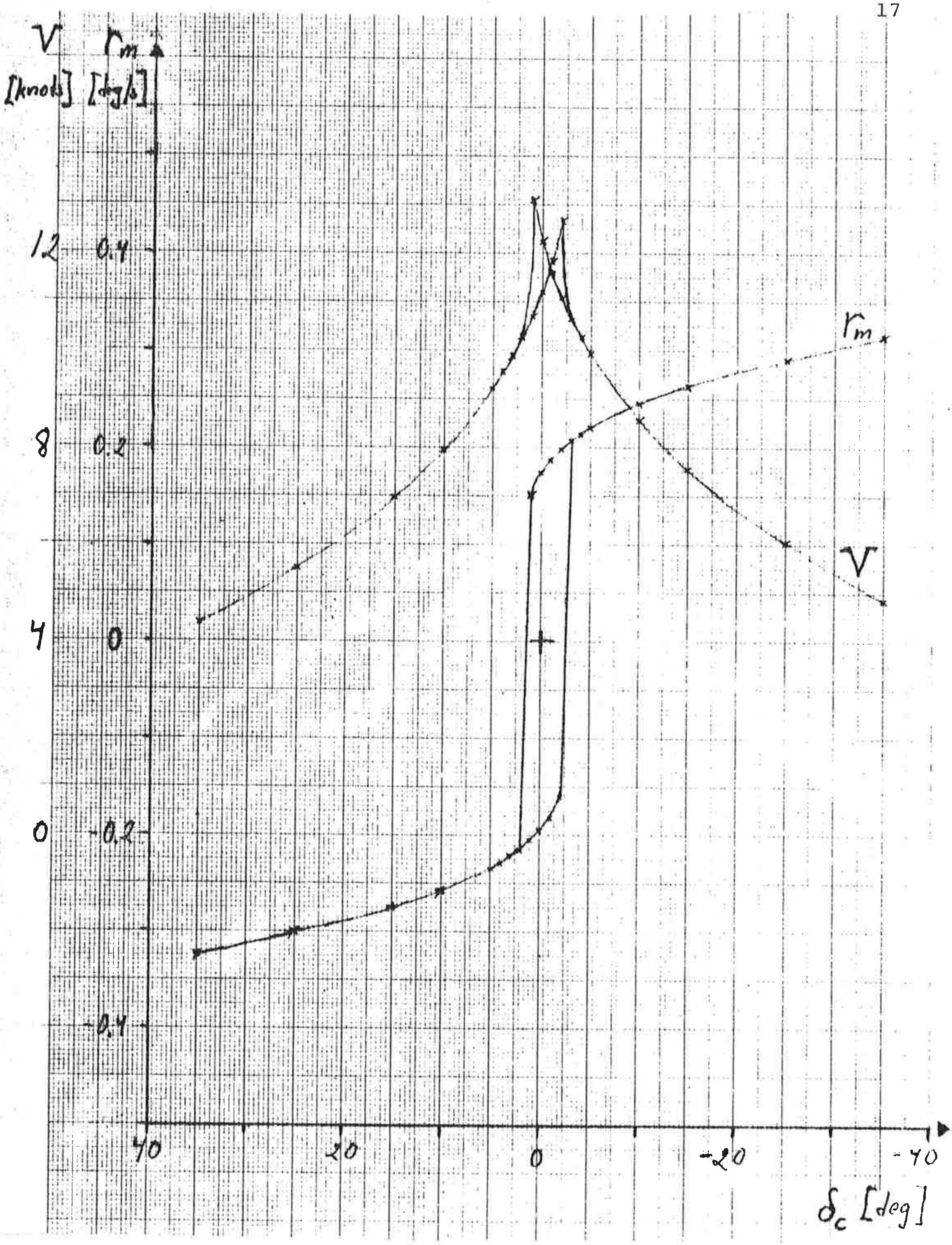


Fig. 4.5 - Spiral test: T = 22.3 m.

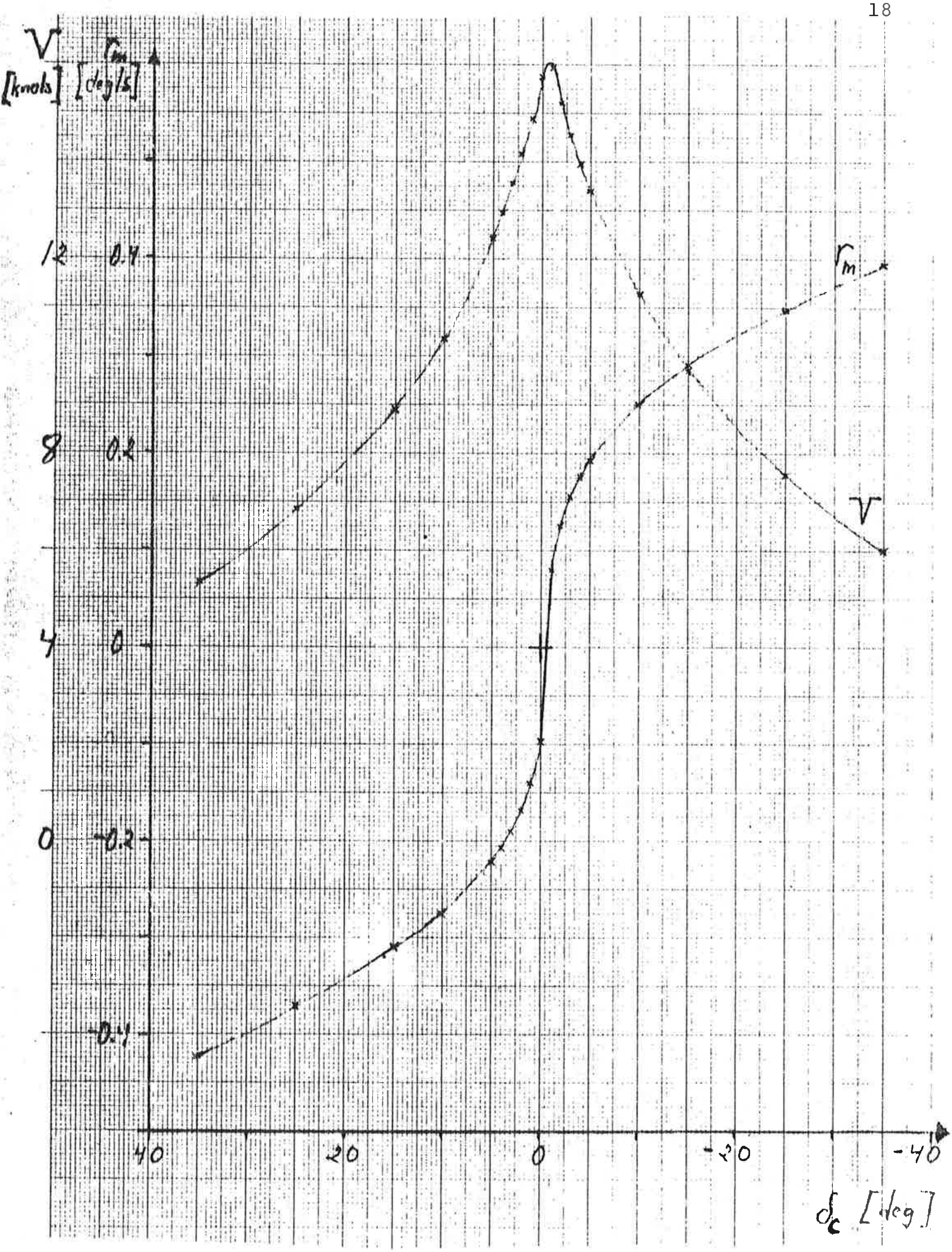


Fig. 4.6 - Spiral test: T = 10.5 m.

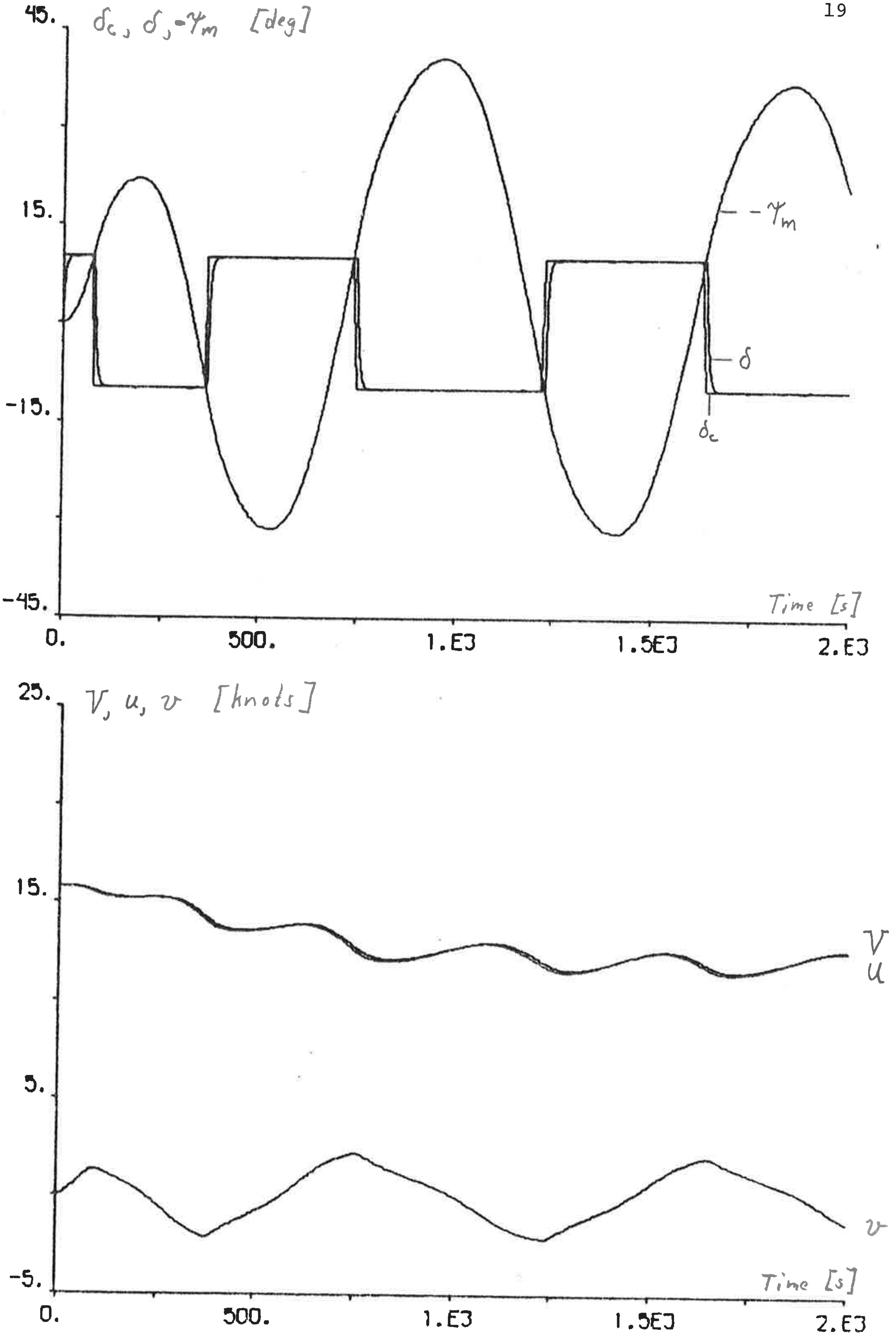


Fig. 4.7 a - Zig-zag test ($10^\circ/10^\circ$): T = 22.3 m.

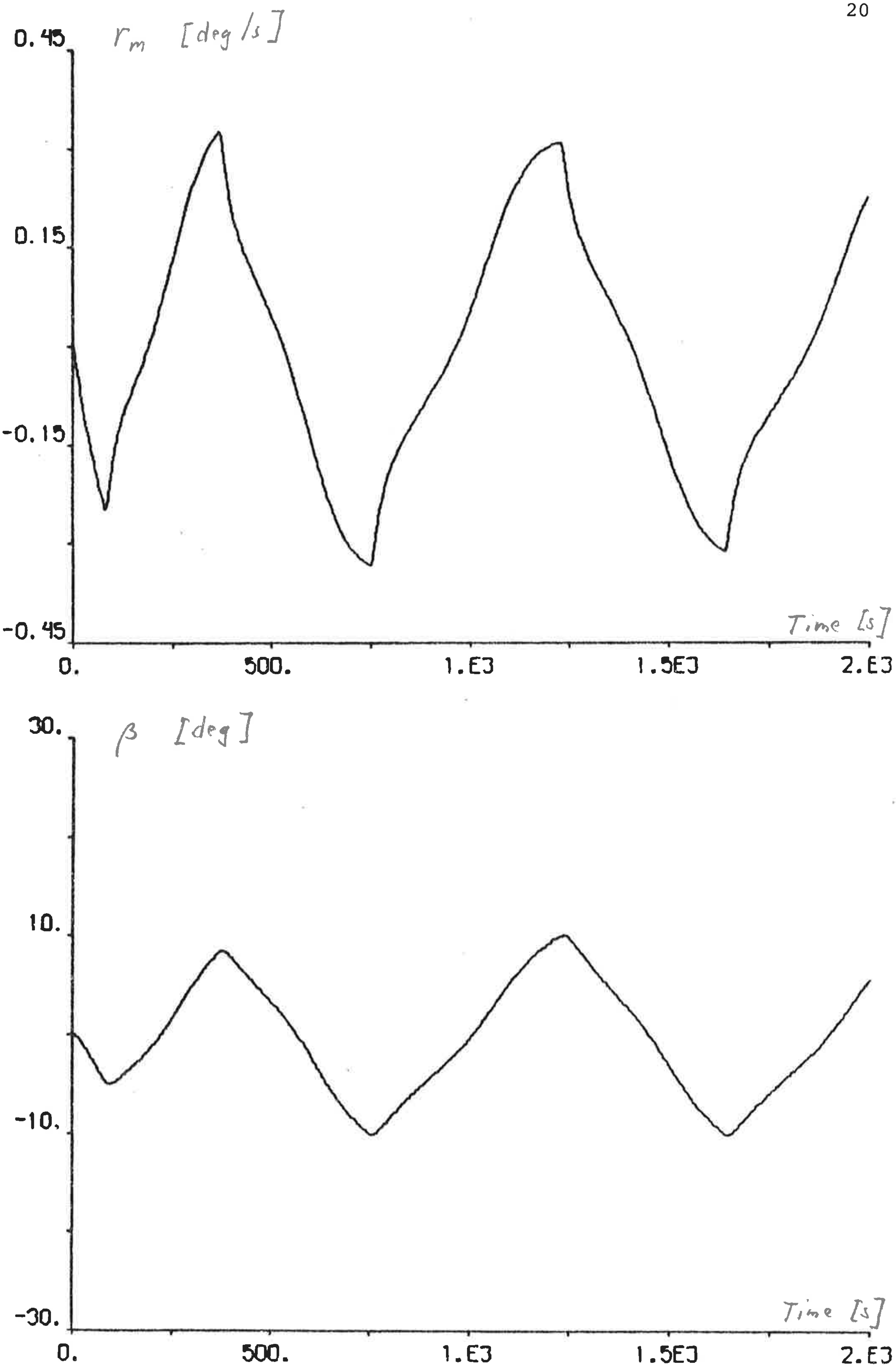

0.45
r_m [deg/s]
0.15
-0.15
-0.45
Time [s]
0.
500.
1.E3
1.5E3
2.E3
30.
β [deg]
10.
-10.
-30.
Time [s]
0.
500.
1.E3
1.5E3
2.E3

Fig. 4.7 b

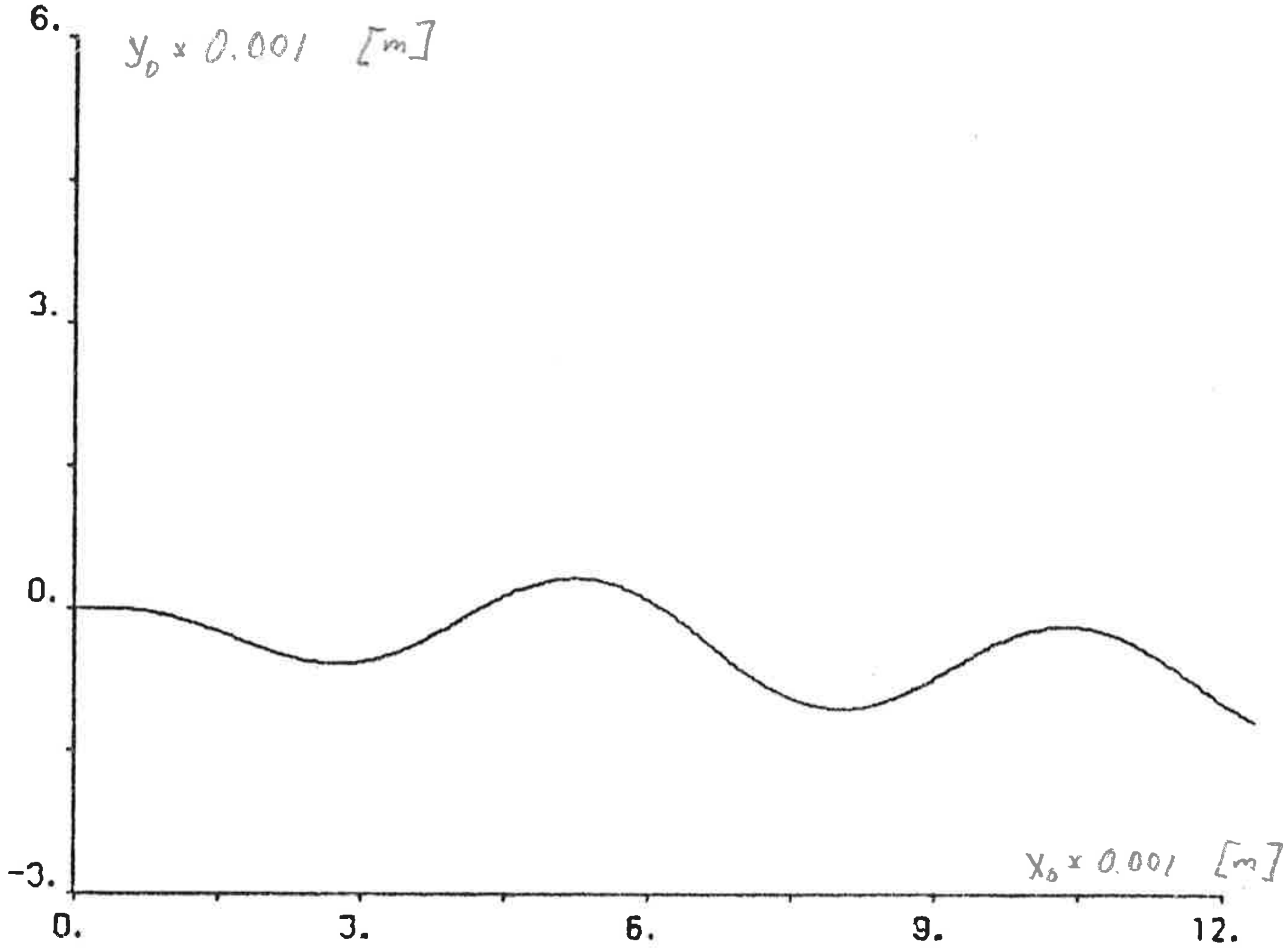
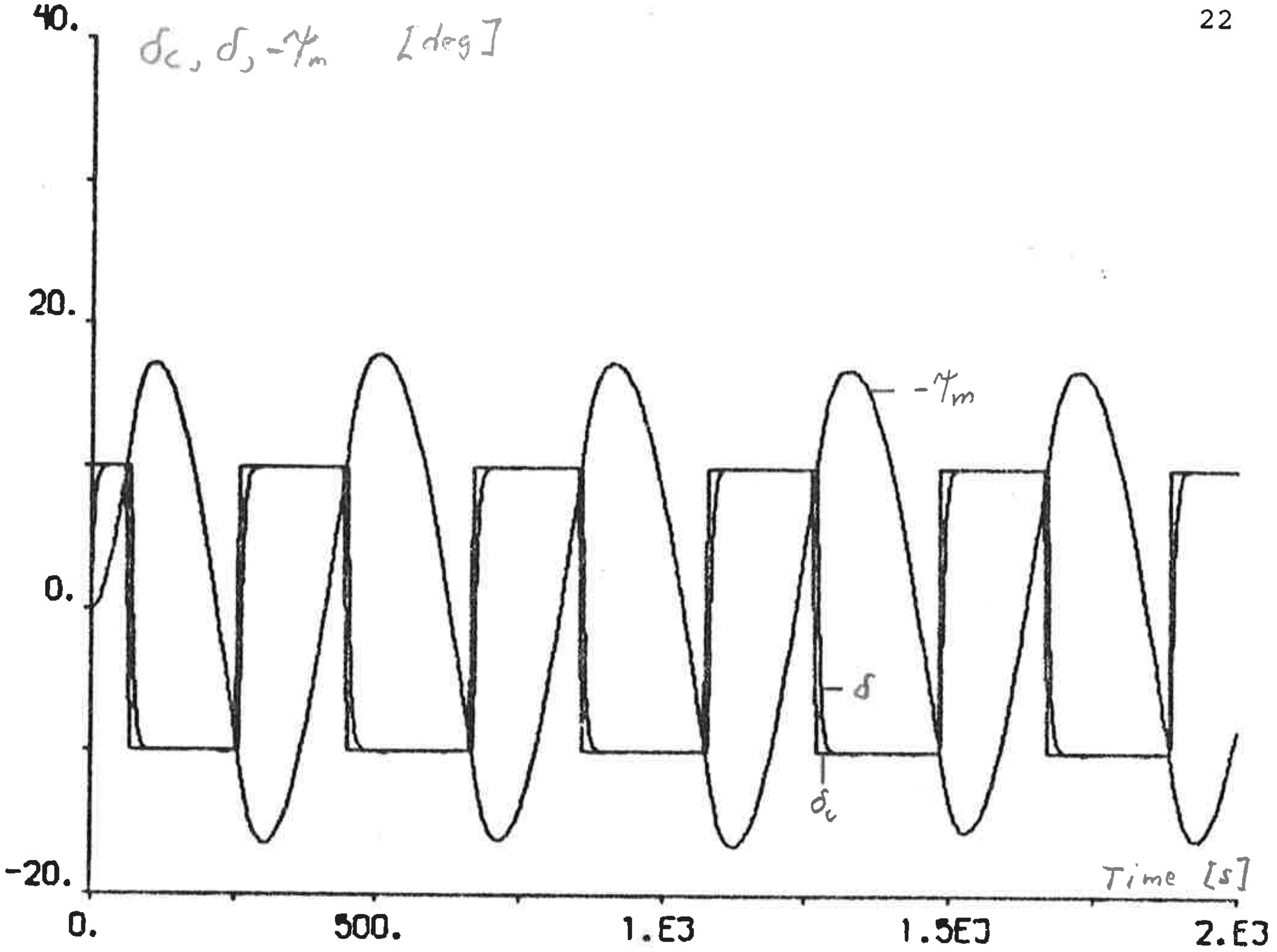


Fig. 4.7 c



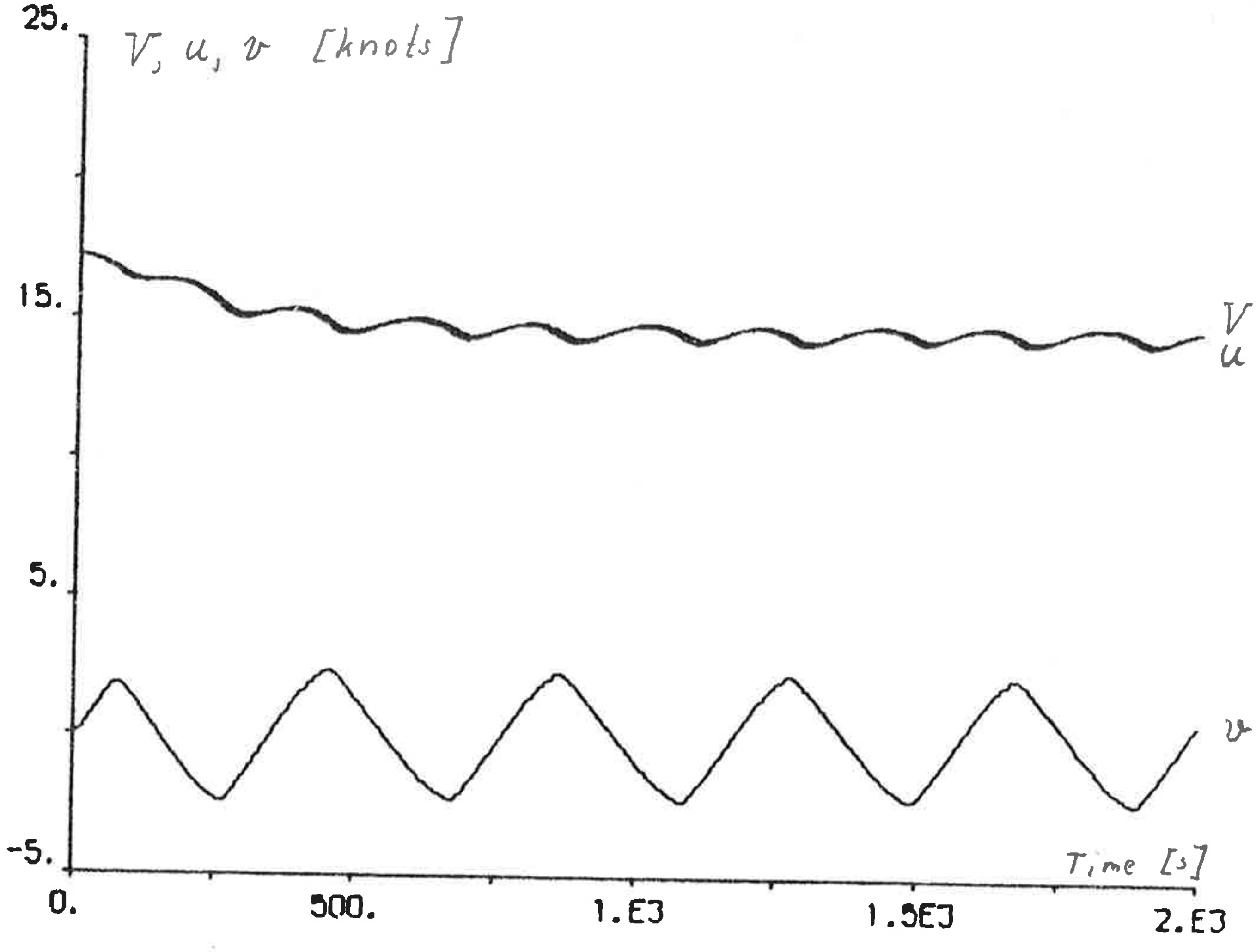


Fig. 4.8 a - Zig-zag test ($10^o/10^o$): T = 10.5 m.

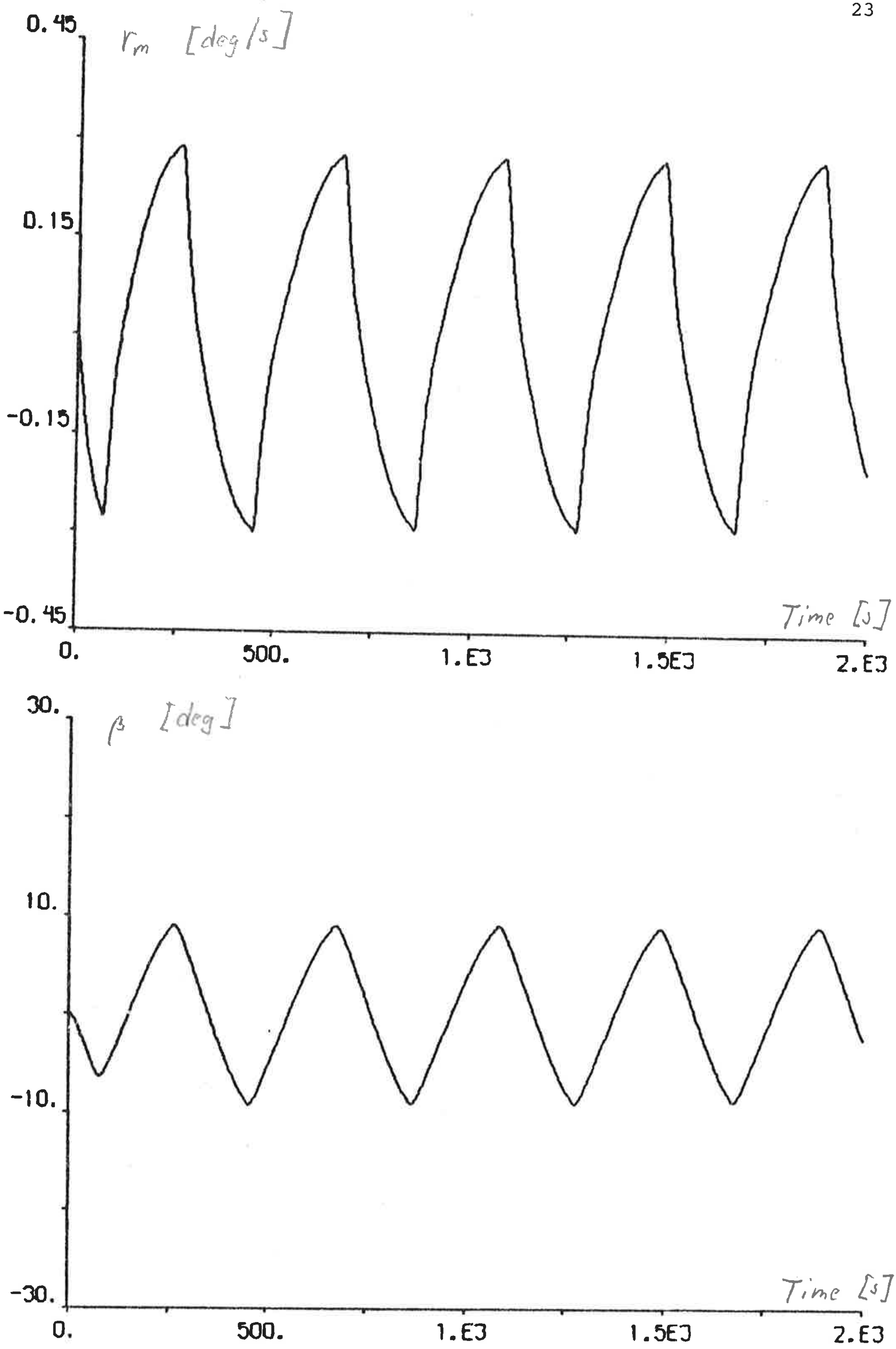

0.45
r_m [deg/s]
0.15
-0.15
-0.45
Time [s]
0.
500.
1.E3
1.5E3
2.E3
30.
β [deg]
10.
-10.
-30.
Time [s]
0.
500.
1.E3
1.5E3
2.E3

Fig. 4.8 b

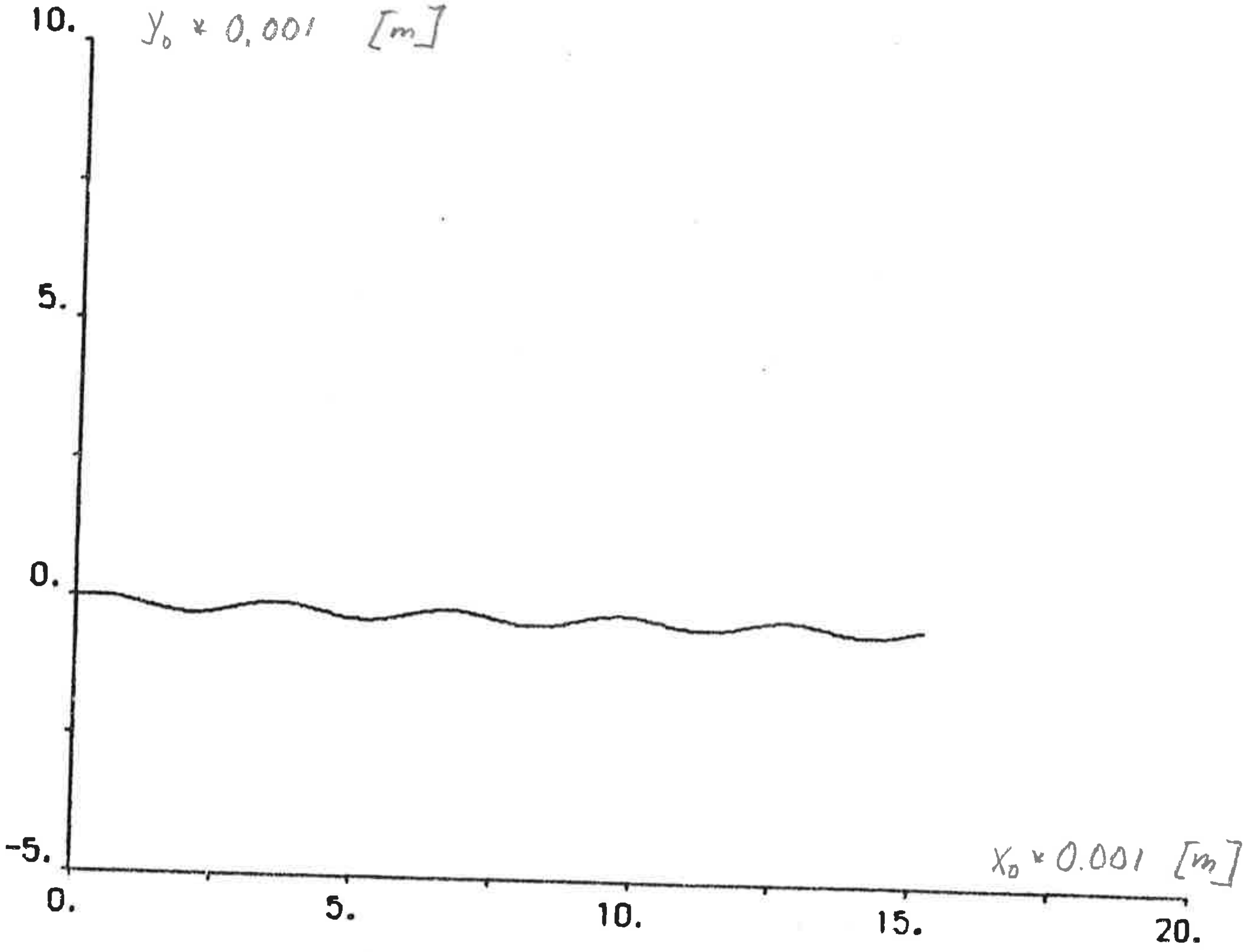


Fig. 4.8 c

5. SIMULATION OF YAWS

The yaw regulator described in Chapter 3 is used to perform course changes $\Delta\psi_{ref}$ of 2, 4, 45 and 120 deg when the mean draught of the ship T is 22.3 m and 10.5 m. The reference values of the yaw rate used in the simulations are $r_{ref} = 0.05$, 0.1, 0.2 and 0.3 deg/s. The initial reference course is always equal to 0 deg and the course change is requested after 100 s.

Simulations when no disturbances are applied, i.e. $F_w = 0$, $w_1 = w_2 = e_1 = e_2 = 0$, are shown in Figs. 5.1 - 5.14. Constant wind force disturbance ($F_w = 0.002$ m/s^2, $w_1 = w_2 = e_1 = e_2 = 0$) is used in Figs. 5.15 - 5.22. Finally, stochastic disturbances (cf. Chapter 2) are applied in the simulations of Figs. 5.23 - 5.32 ($\sigma_r = 0.01$ deg/s) and Figs. 5.33 - 5.42 ($\sigma_r = 0.02$ deg/s). The angle of the wind direction α is equal to 90 deg or 270 deg. The upper curves of each figure show the result when the first parameter set of the yaw regulator (cf. Chapter 3) is used, the lower curves show the result when the second parameter set is used. The following scalings are performed before the plotting:

$$10 \times \psi_m, \quad 10 \times \psi_{ref}, \quad 100 \times r_m, \quad 100 \times r_{ref}, \quad -8 \times M_y$$

when

$$\Delta\psi_{ref} = 2 \text{ or } 4 \text{ deg},$$

and

$$200 \times r_m, \quad 200 \times r_{ref} \quad \text{and} \quad -8 \times M_y$$

when

$$\Delta\psi_{ref} = 45 \quad \text{or} \quad 120 \text{ deg}.$$

The rudder command δ_c is always unscaled. In Figs. 5.1, 5.3 and 5.7 are shown a complete description of the plots.

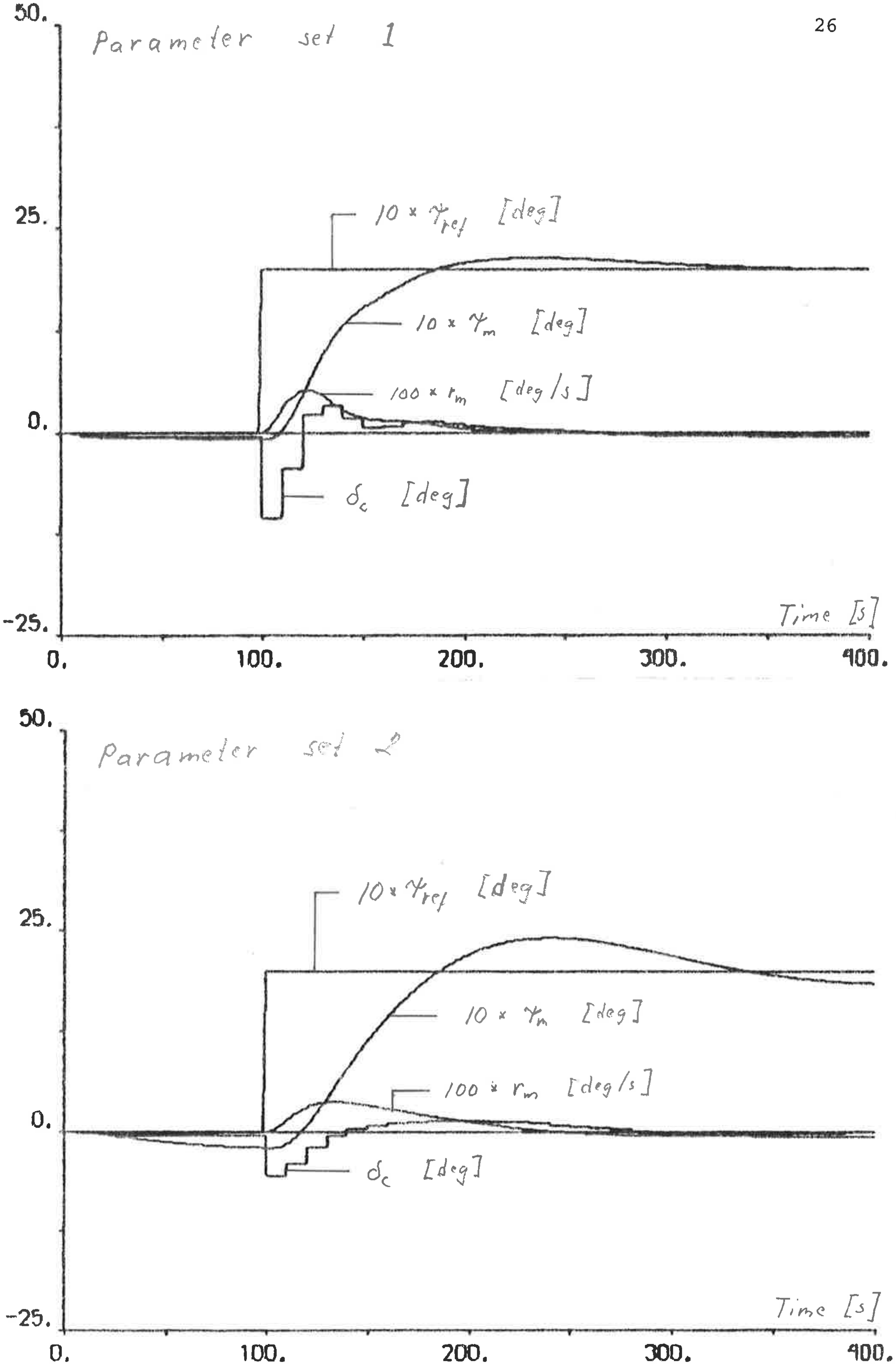


Fig. 5.1 - No disturbances: T = 22.3 m, $\Delta\psi_{ref}$ = 2 deg.

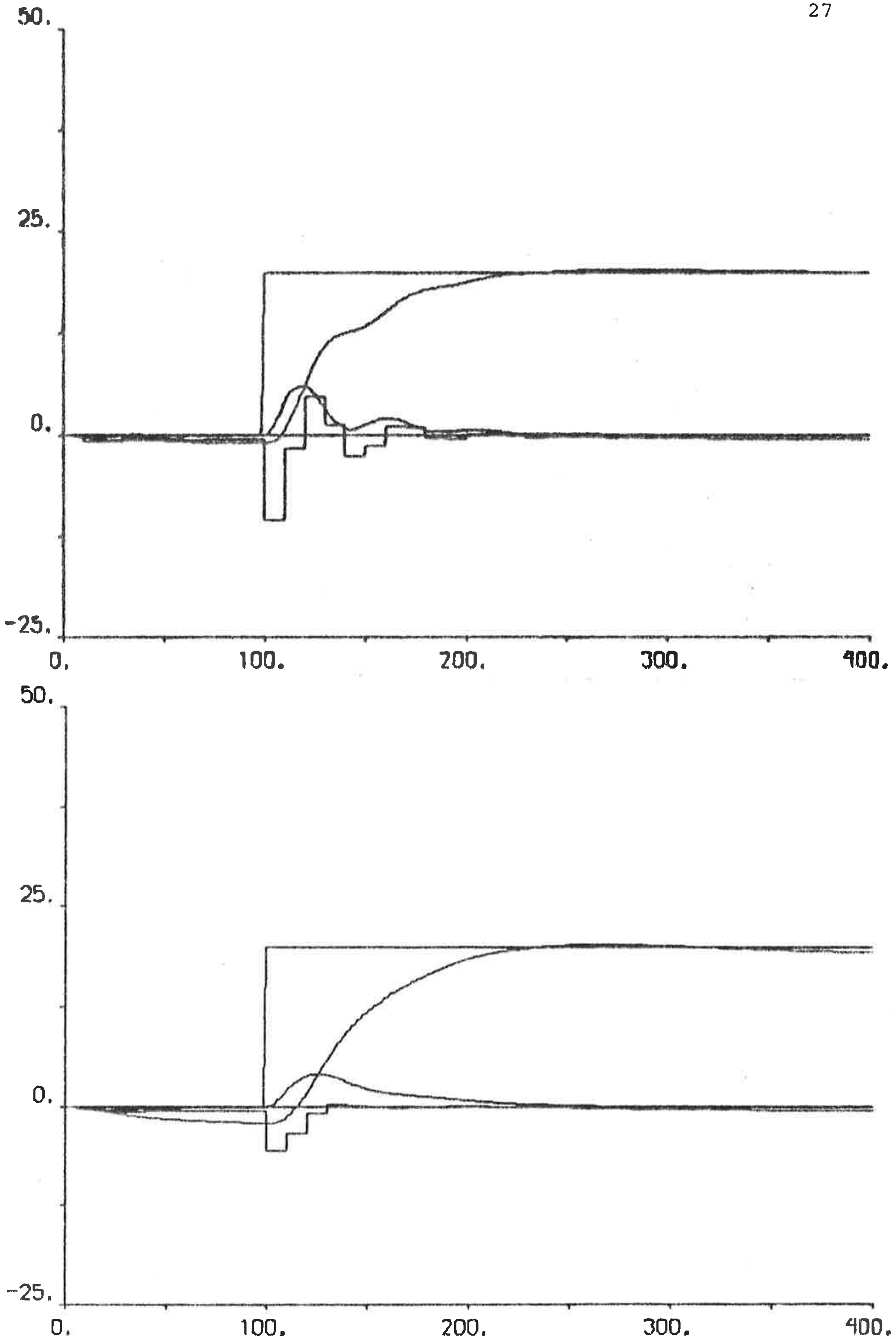
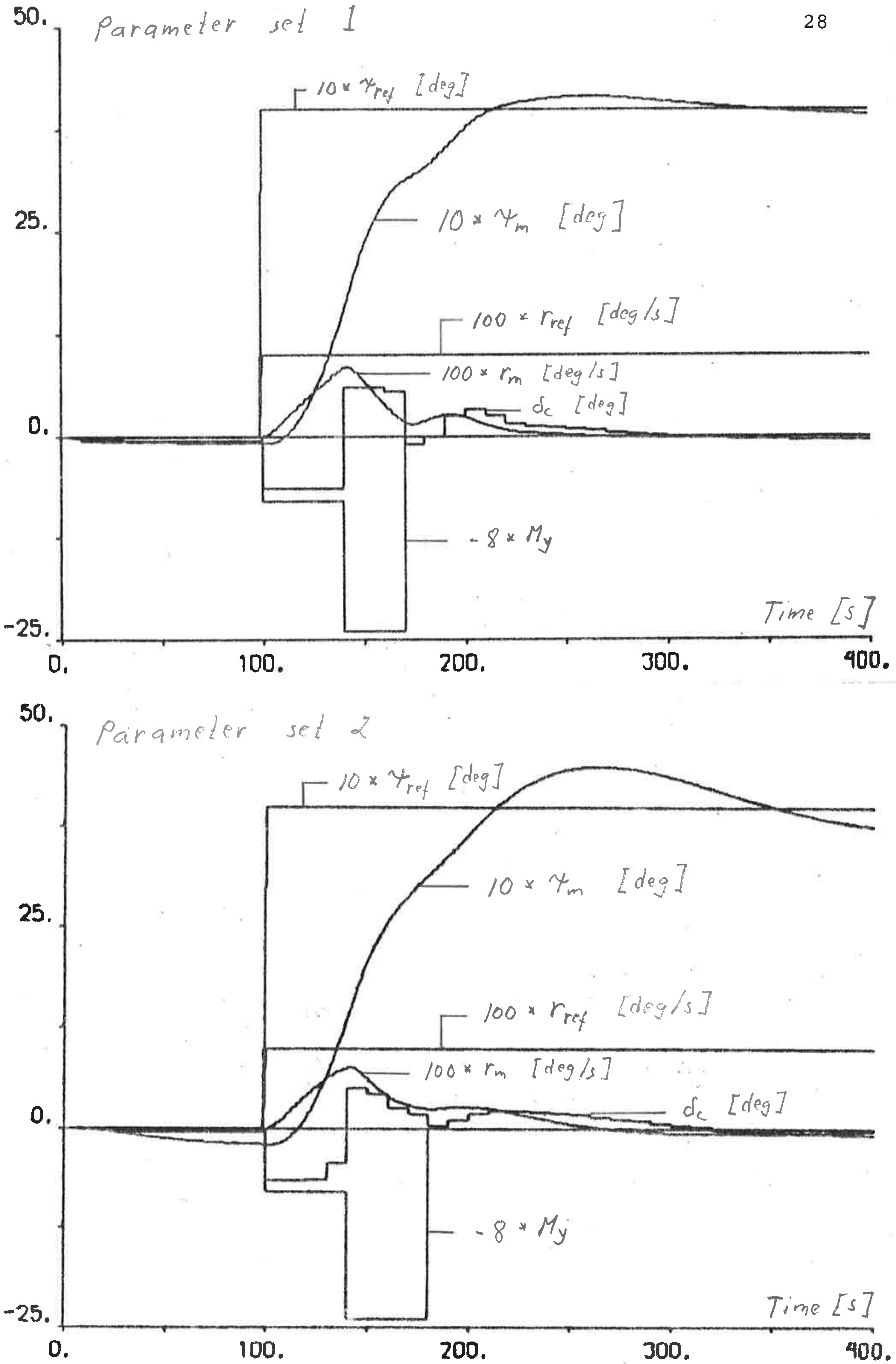
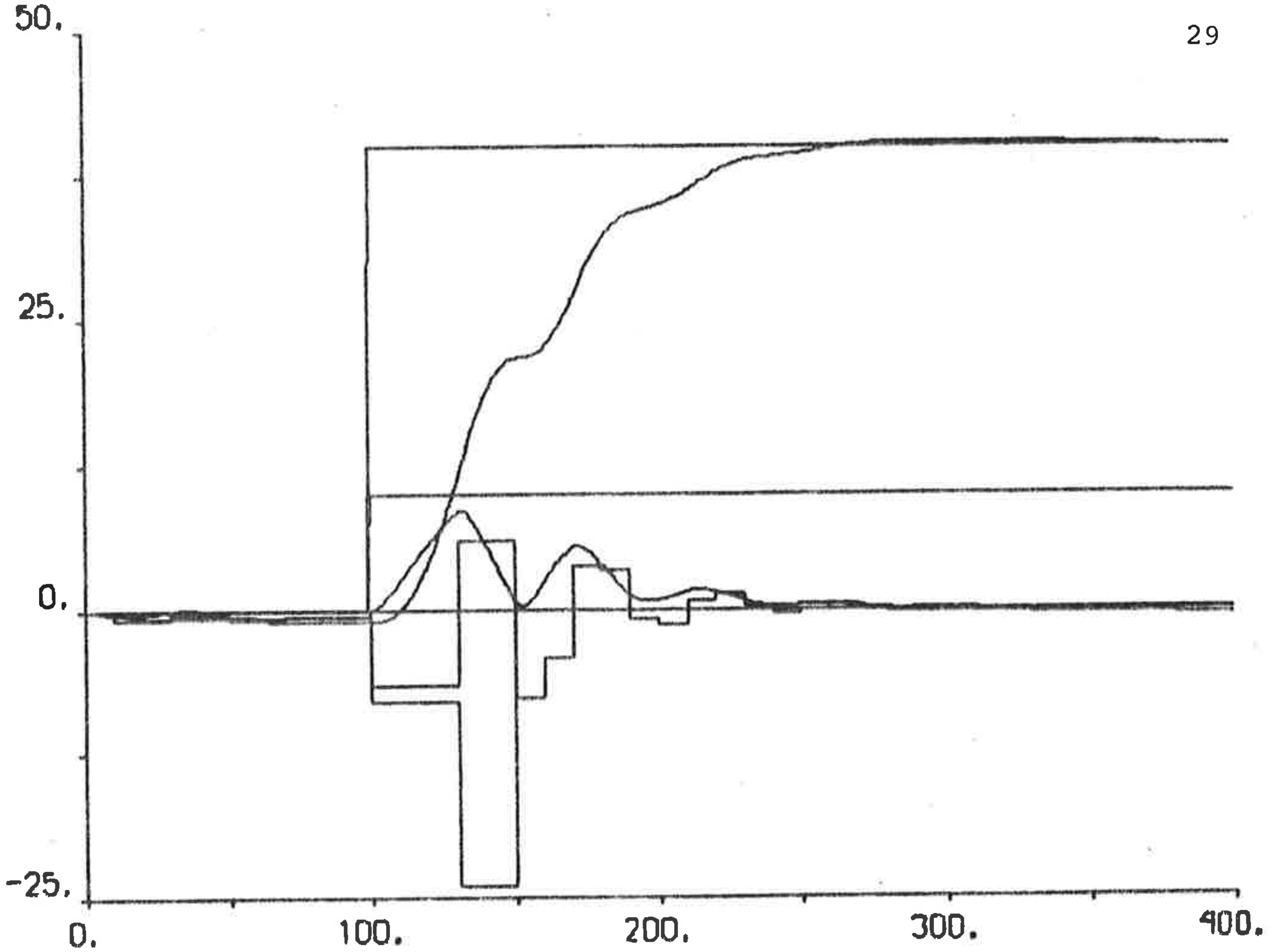


Fig. 5.2 - No disturbances: T = 10.5 m, $\Delta\psi_{ref}$ = 2 deg.



<u>Fig. 5.3</u> - No disturbances: T = 22.3 m, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s.



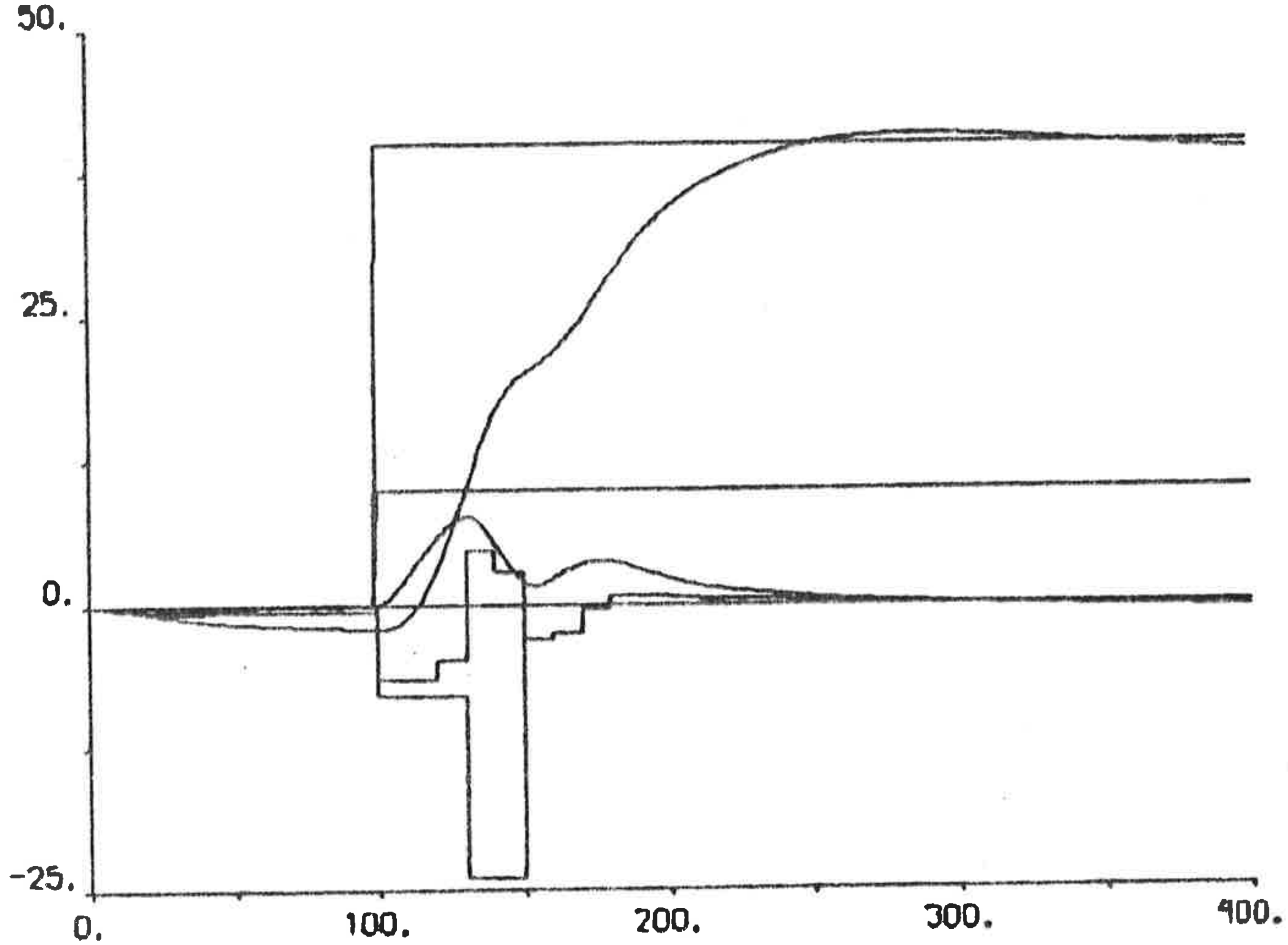
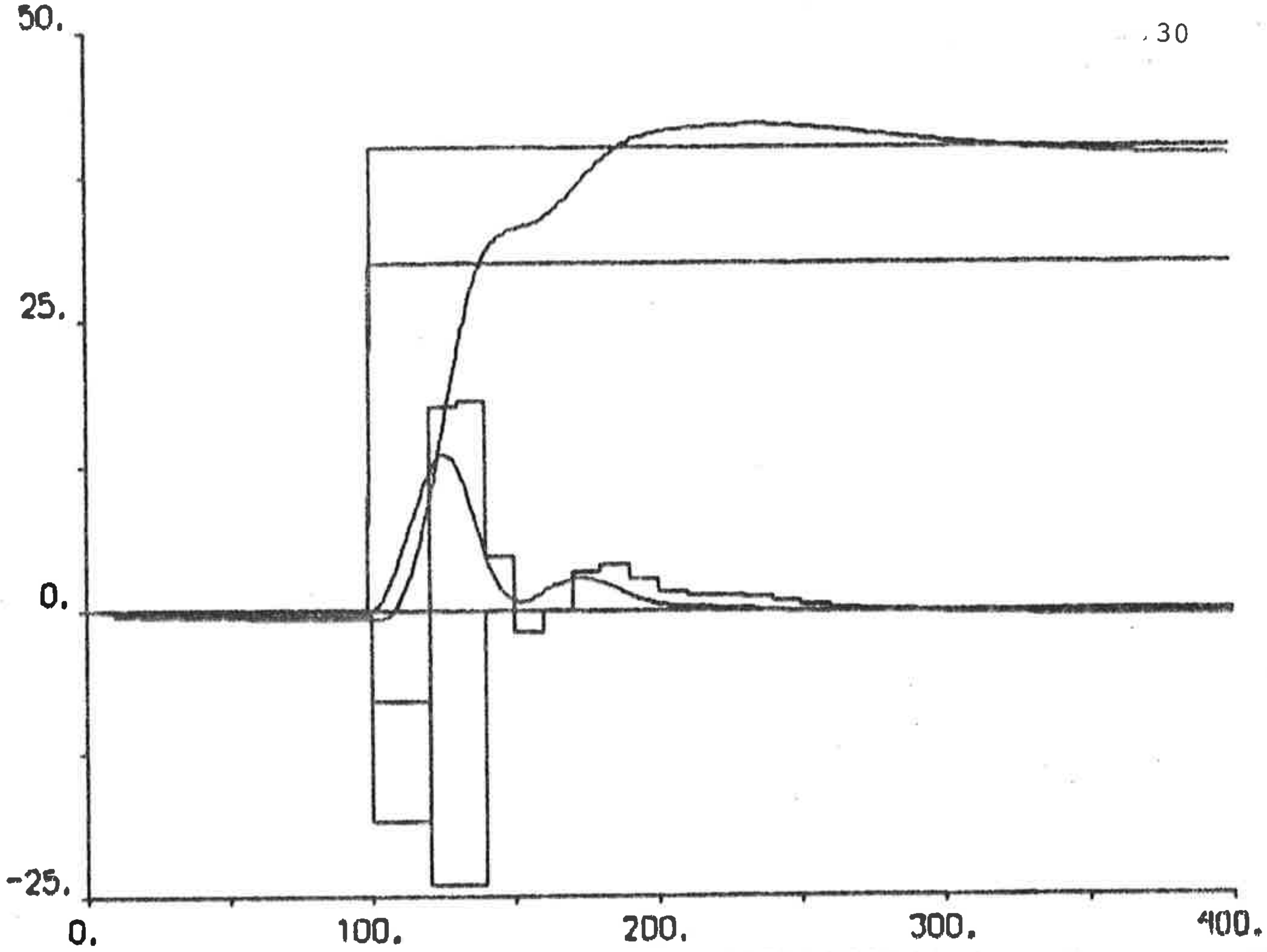


Fig. 5.4 - No dusturbances: T = 10.5 m, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s.



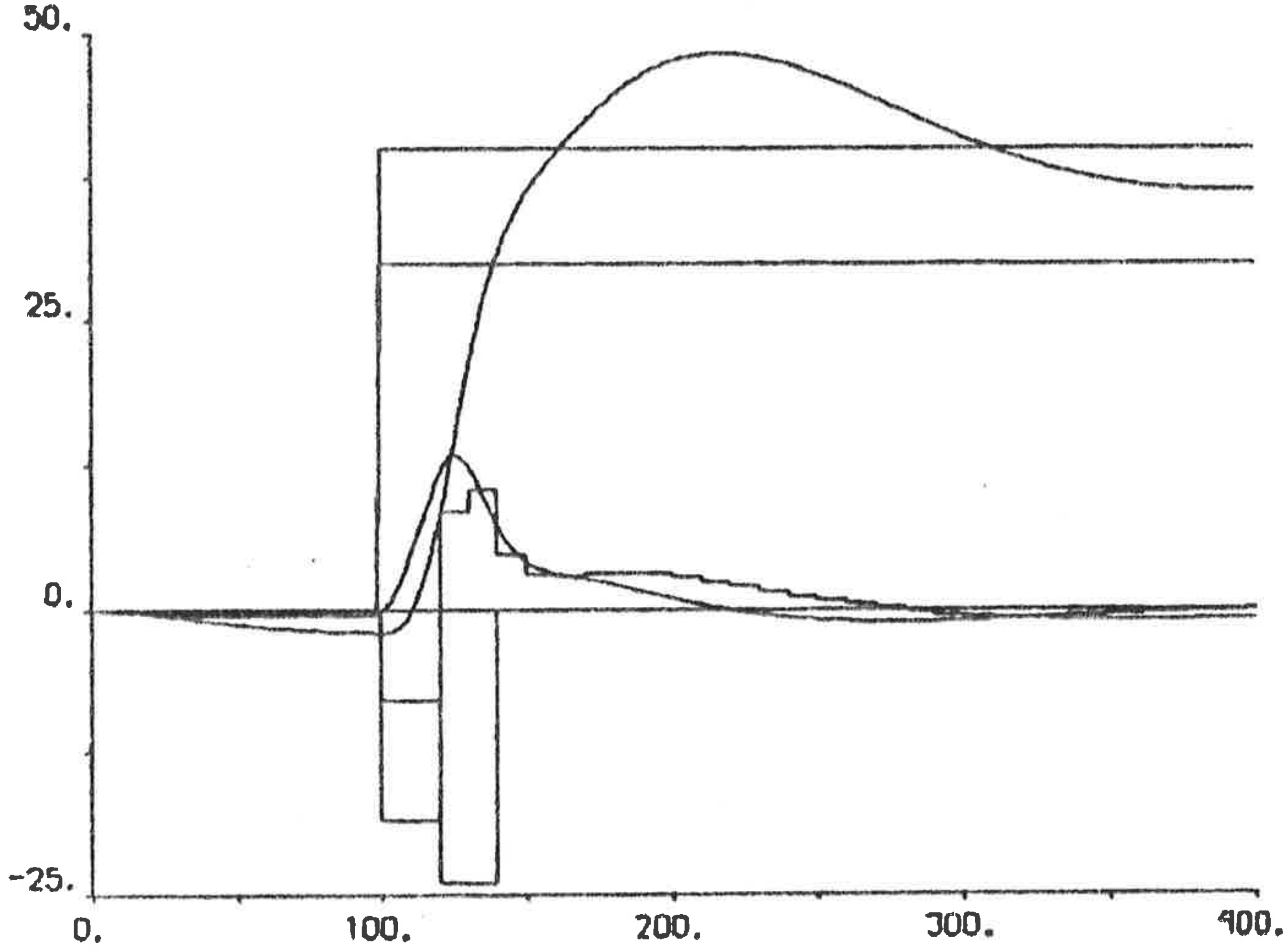


Fig. 5.5 - No disturbances: T = 22.3 m, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.3 deg/s.

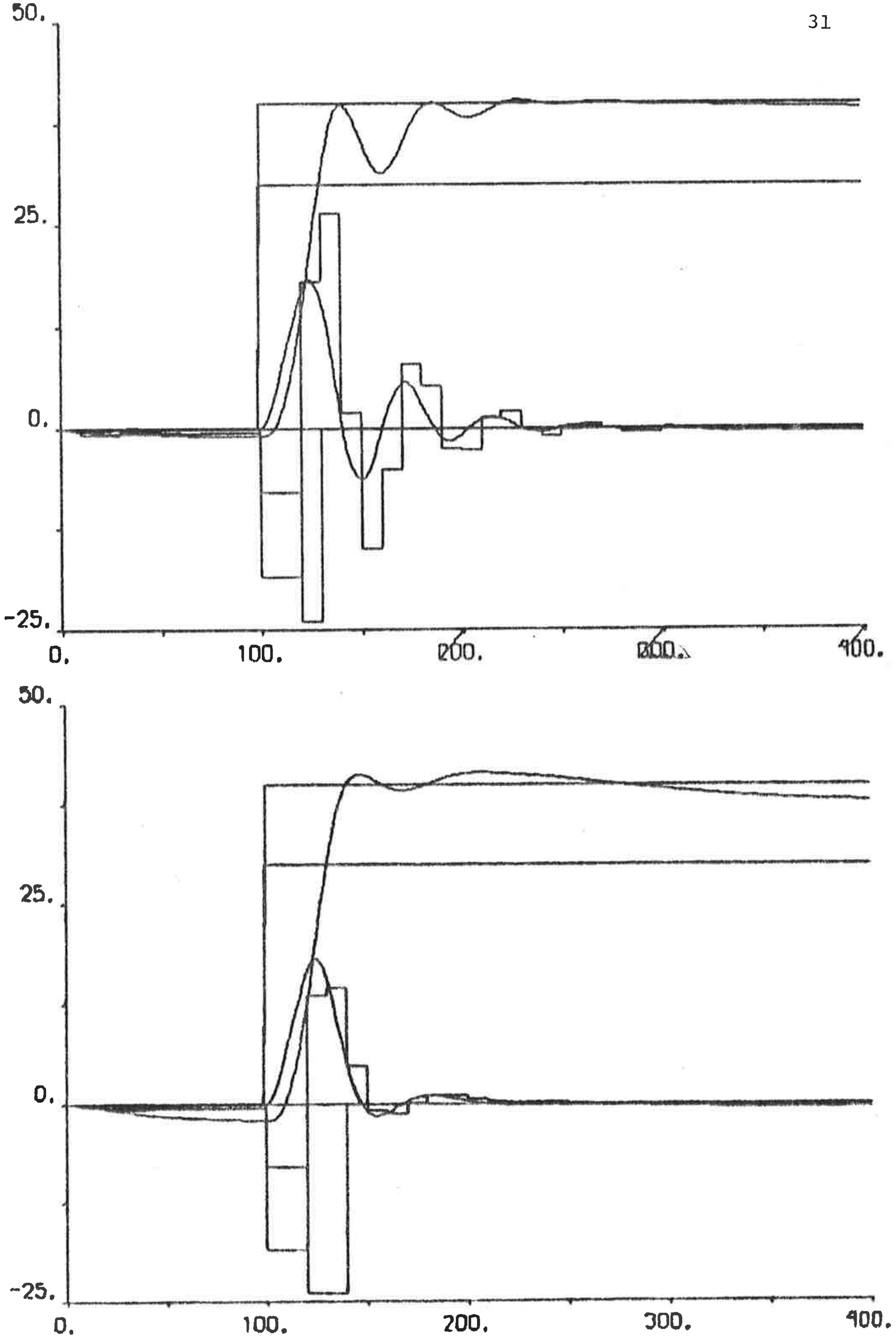


Fig. 5.6 - No disturbances: T = 10.5 m, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.3 deg/s.

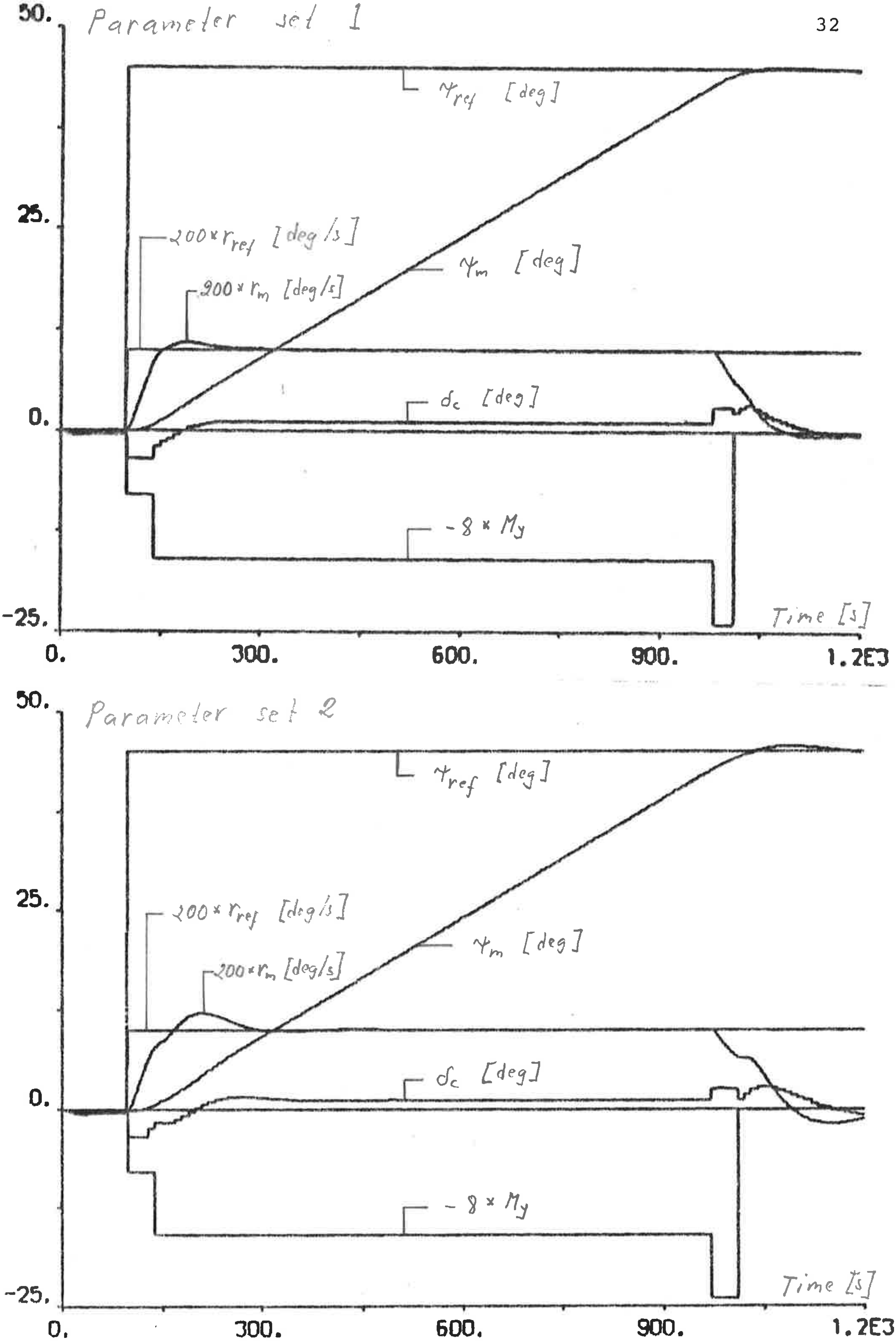


Fig. 5.7 - No disturbances: T = 22.3 m, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.05 deg/s.

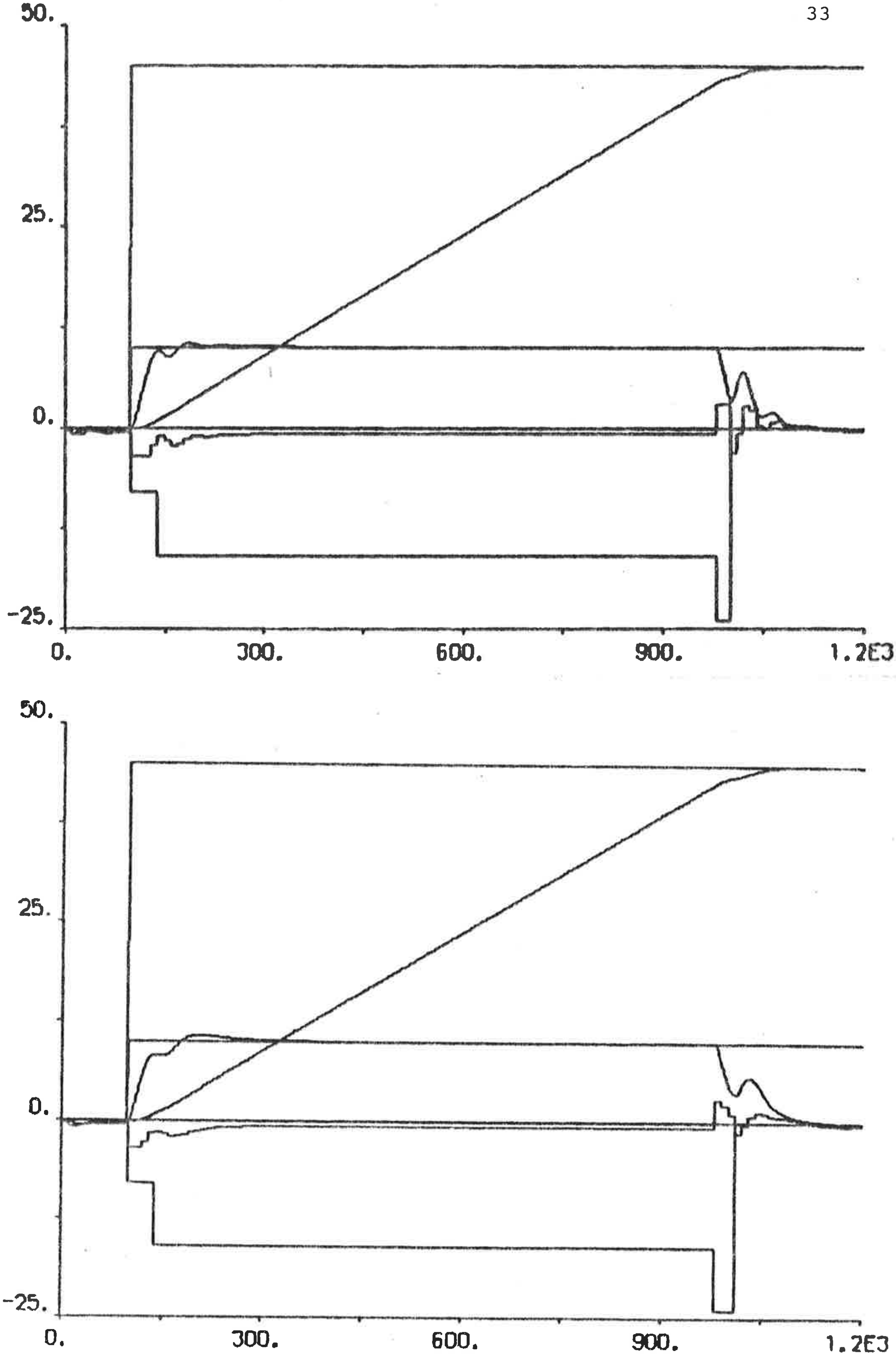


Fig. 5.8 - No disturbances: T = 10.5 m, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.05 deg/s.

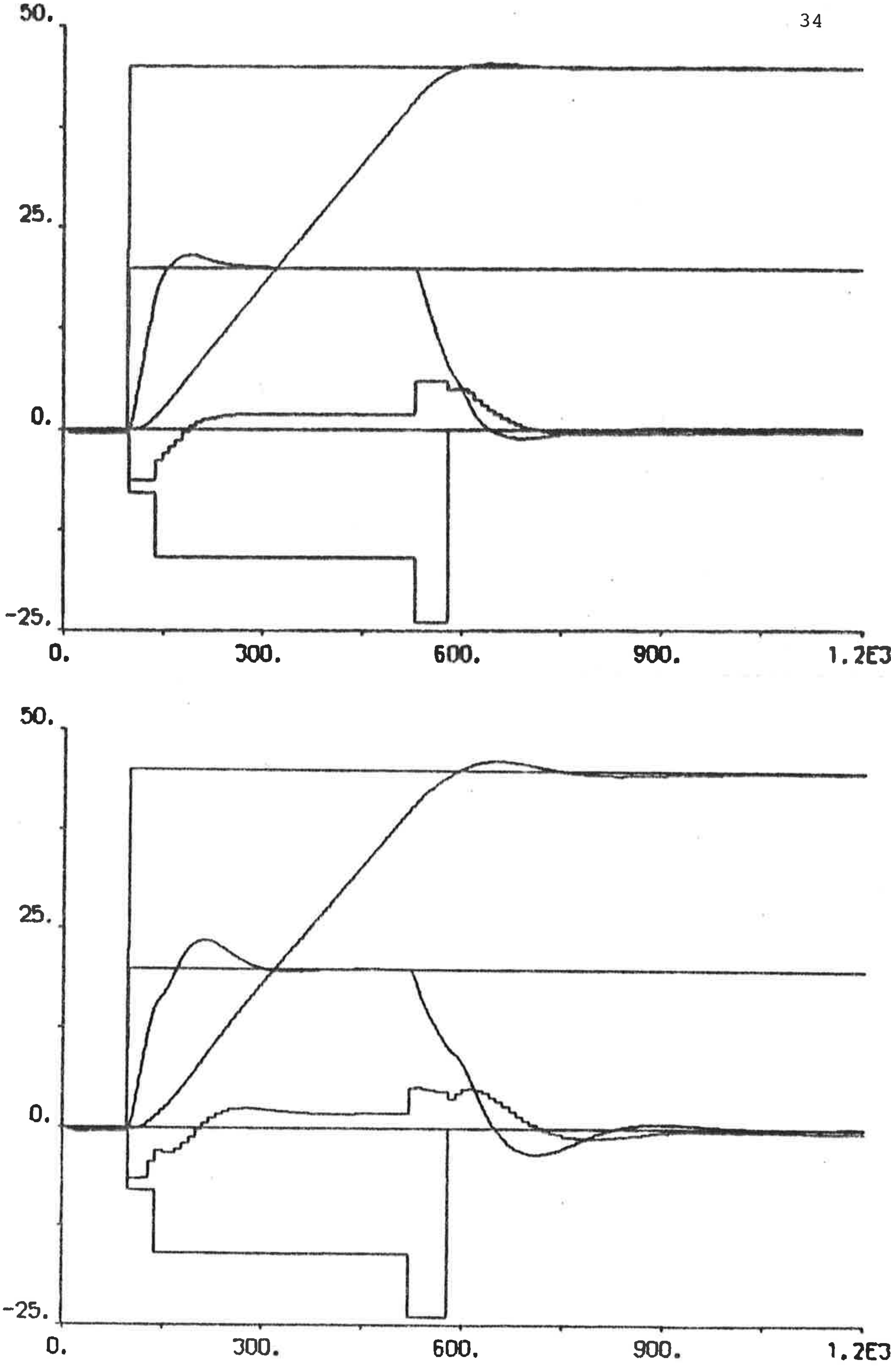


Fig. 5.9 - No disturbances: T = 22.3 m, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s.

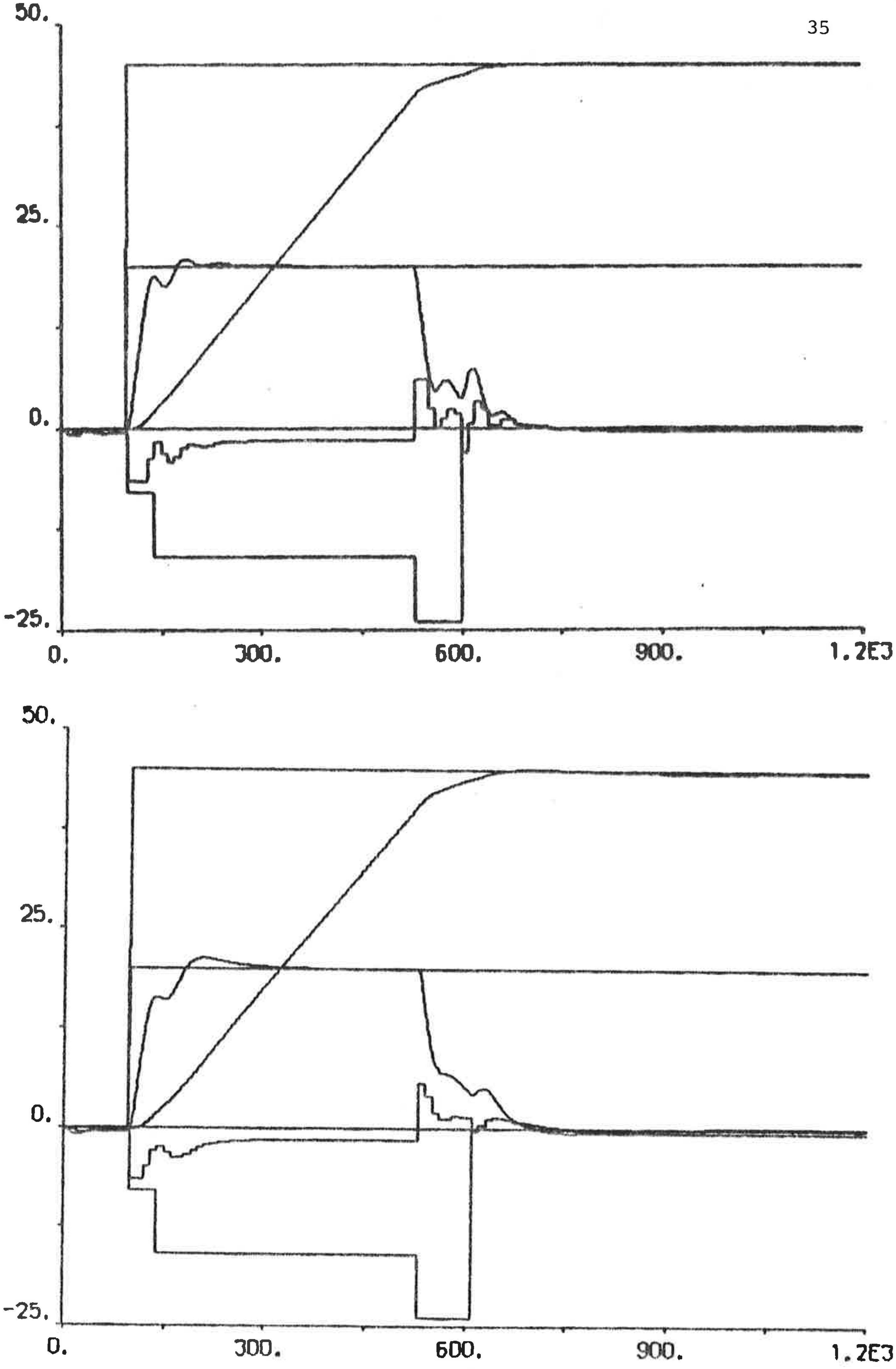


Fig. 5.10 - No disturbances: T = 10.5 m, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s.

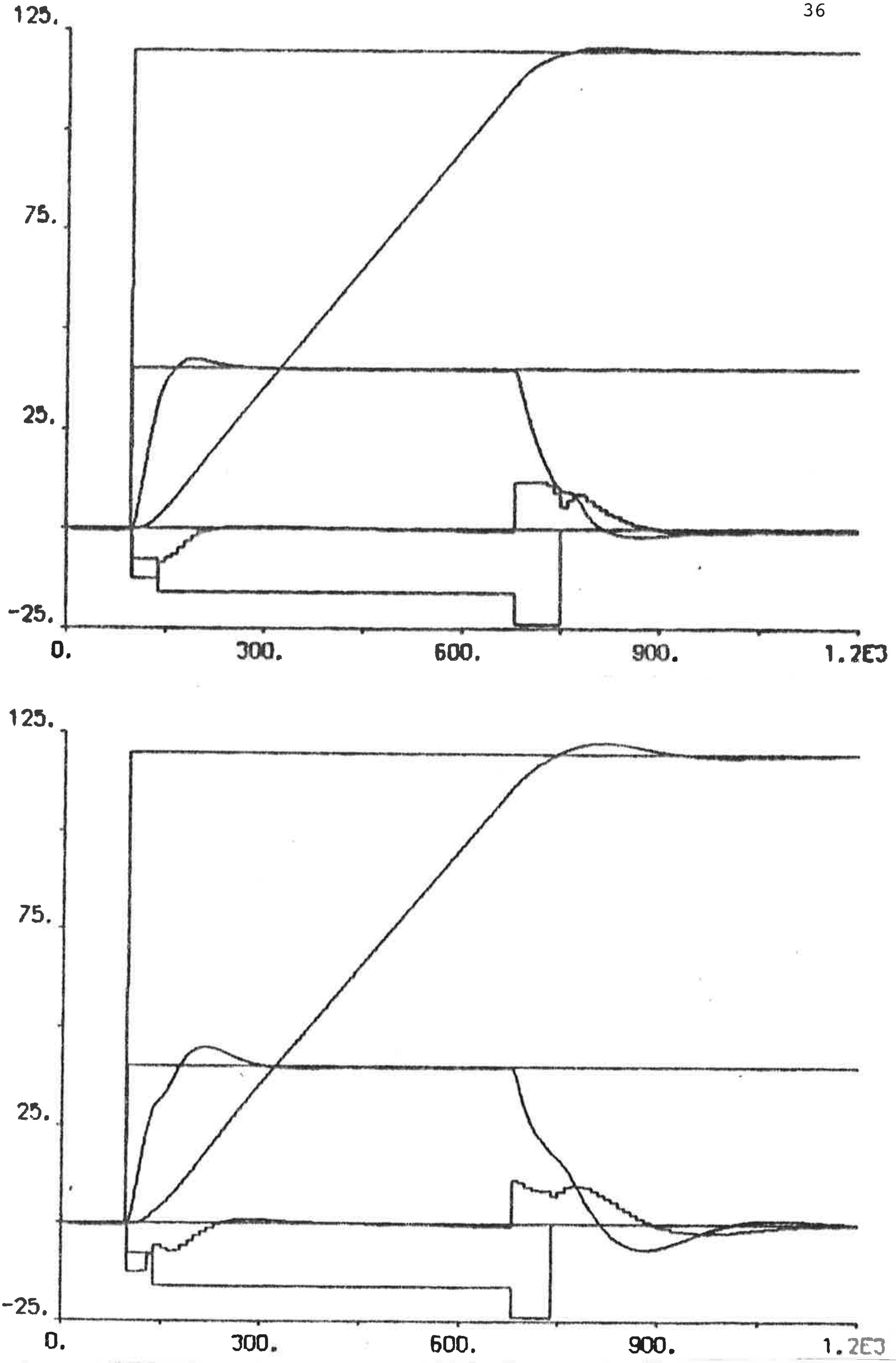
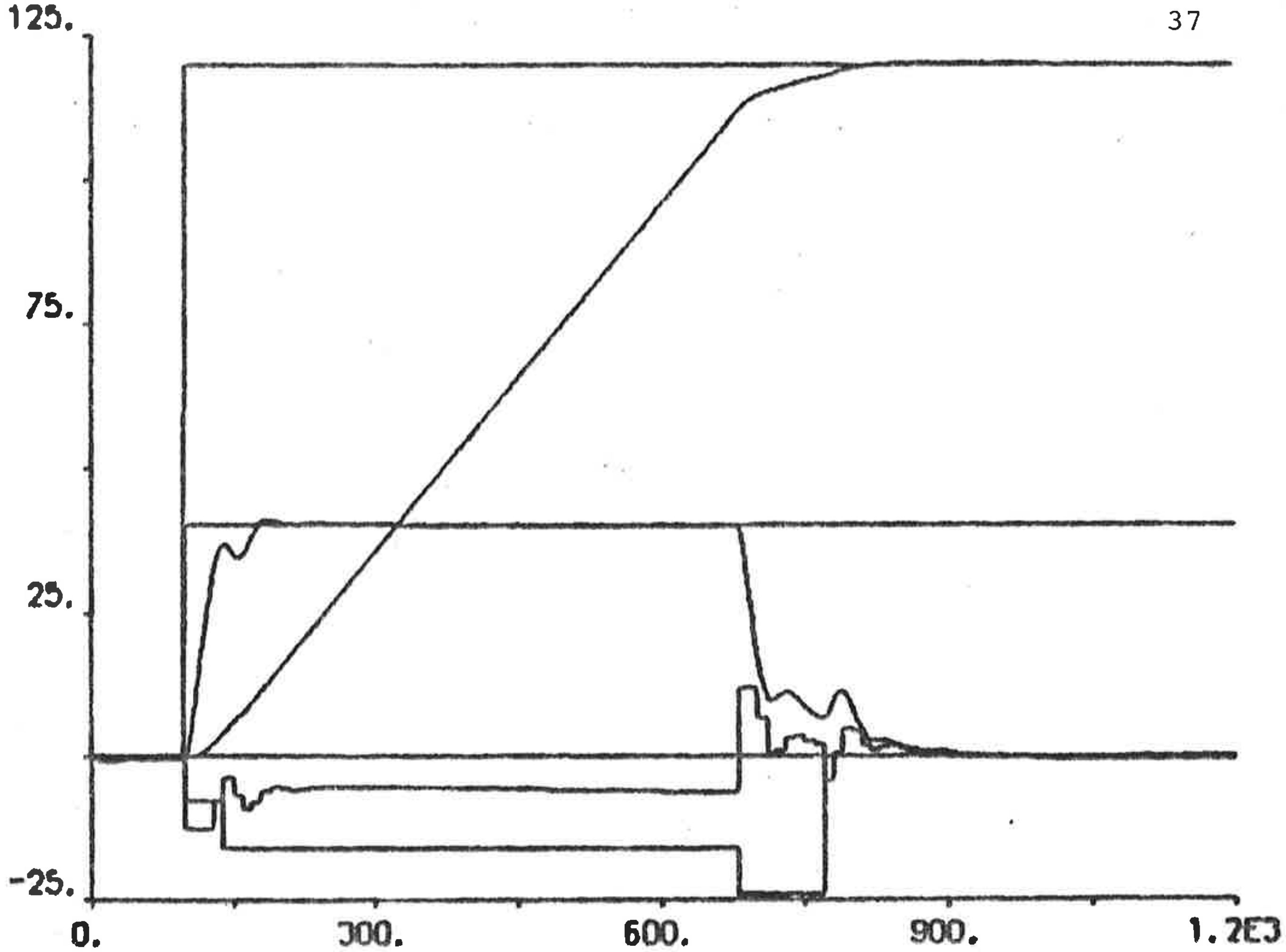


Fig. 5.11 - No disturbances: T = 22.3 m, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.2 deg/s.



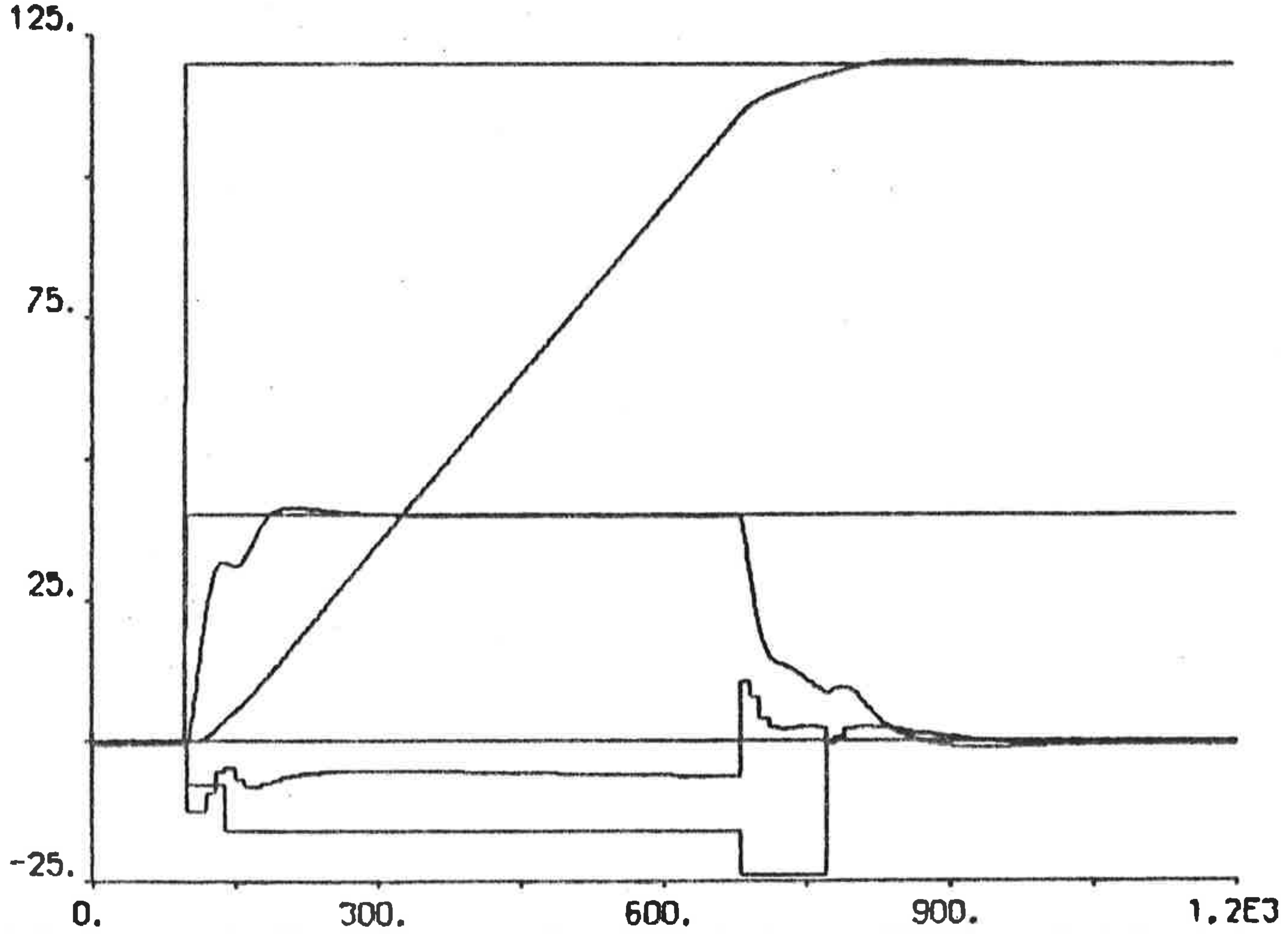


Fig. 5.12 - No disturbances: T = 10.5 m, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.2 deg/s.

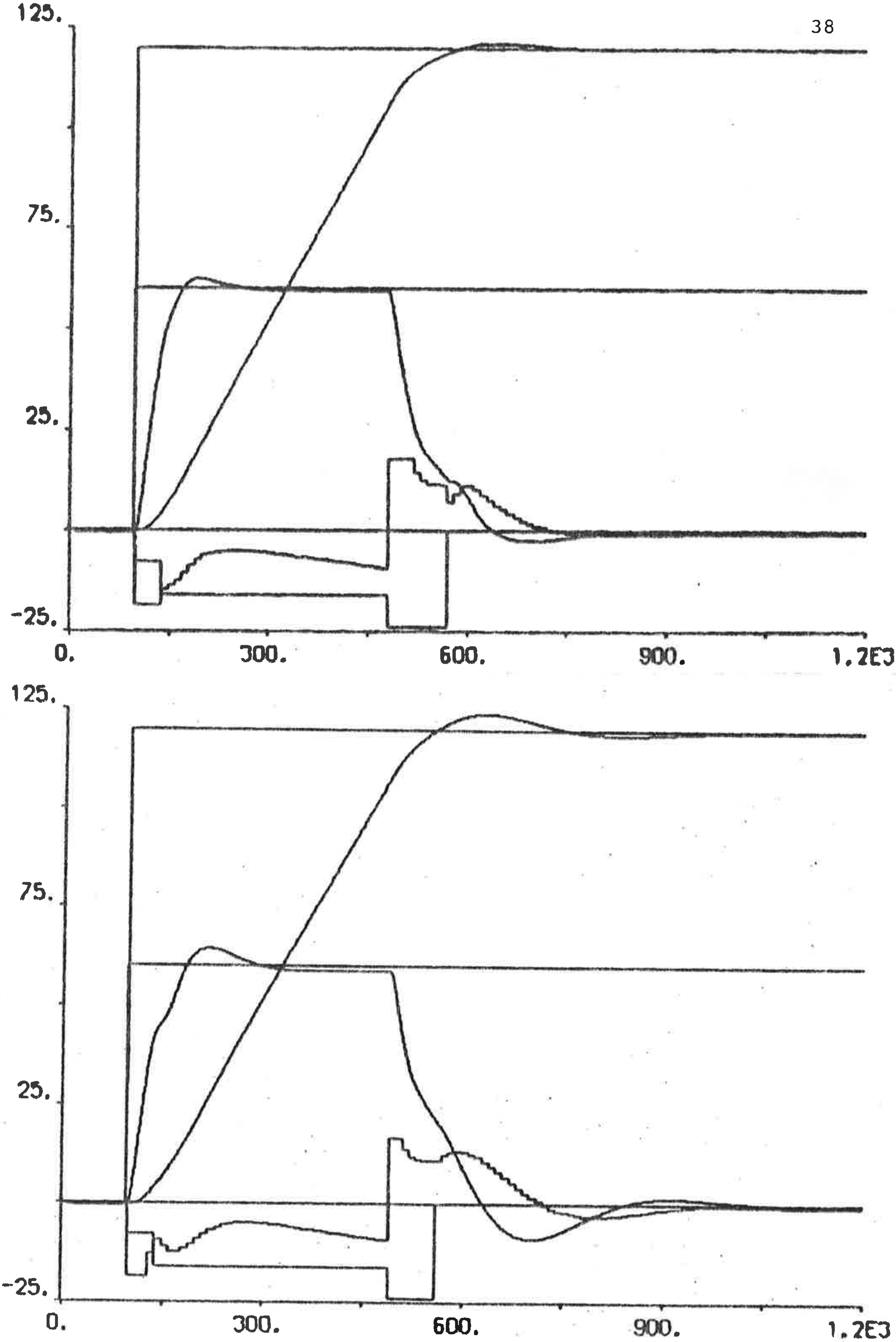


Fig. 5.13 - No disturbances: T = 22.3 m, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.3 deg/s.

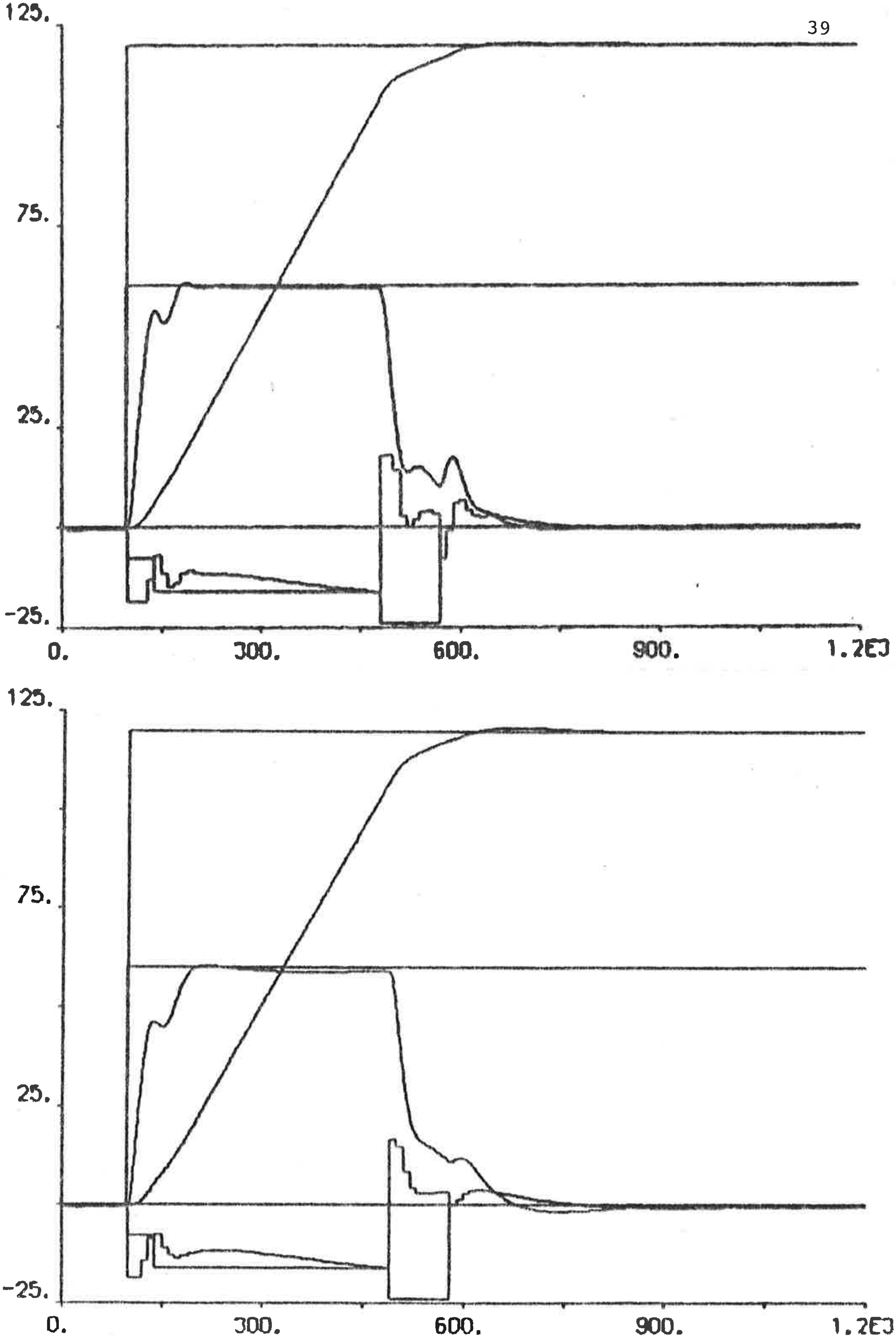
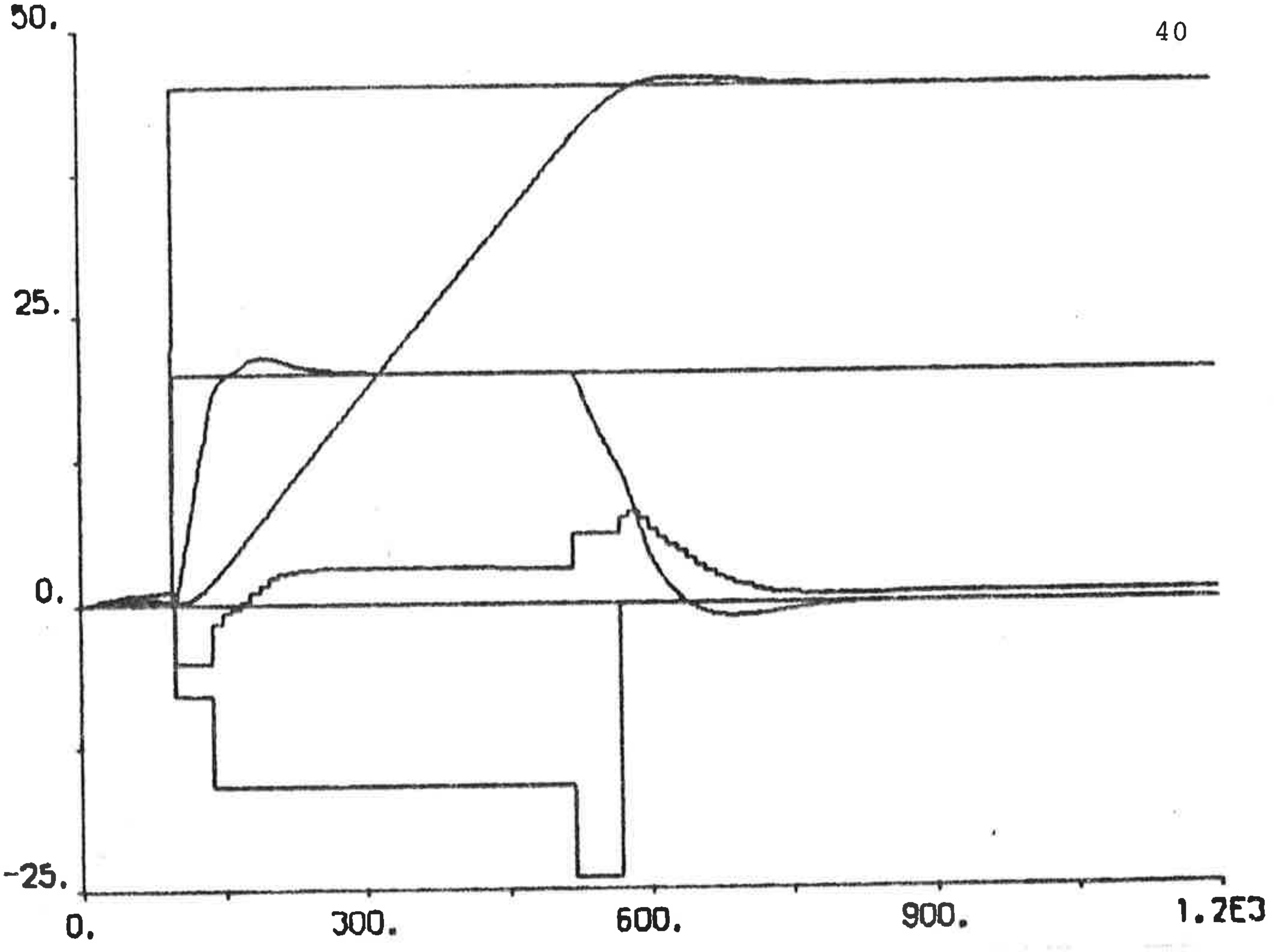


Fig. 5.14 - No disturbances: T = 10.5 m, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.3 deg/s.



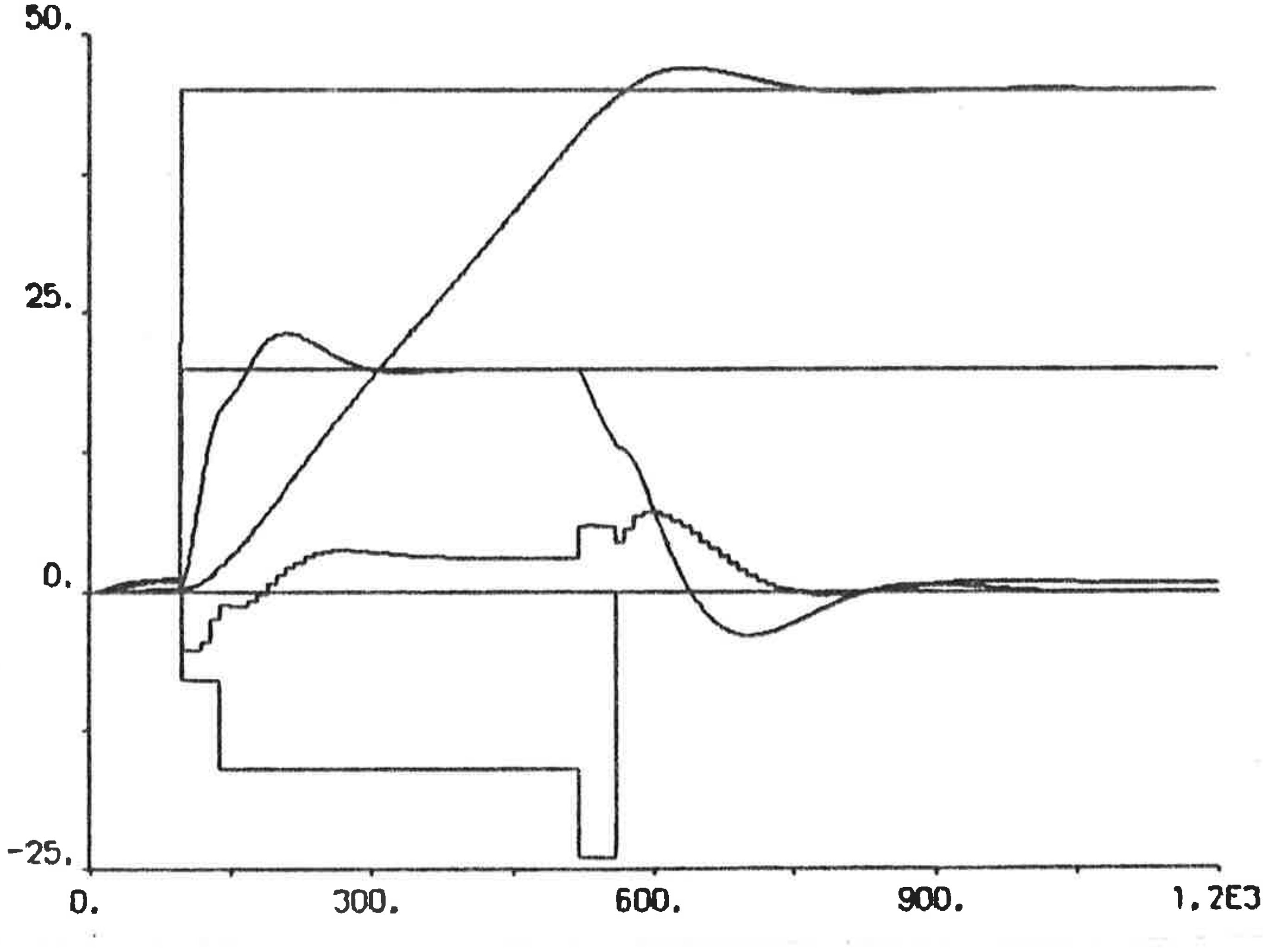


Fig. 5.15 - Constant wind force disturbance: $T = 22.3$ m, $\alpha = 90$ deg, $\Delta\psi_{ref} = 45$ deg, $r_{ref} = 0.1$ deg/s.

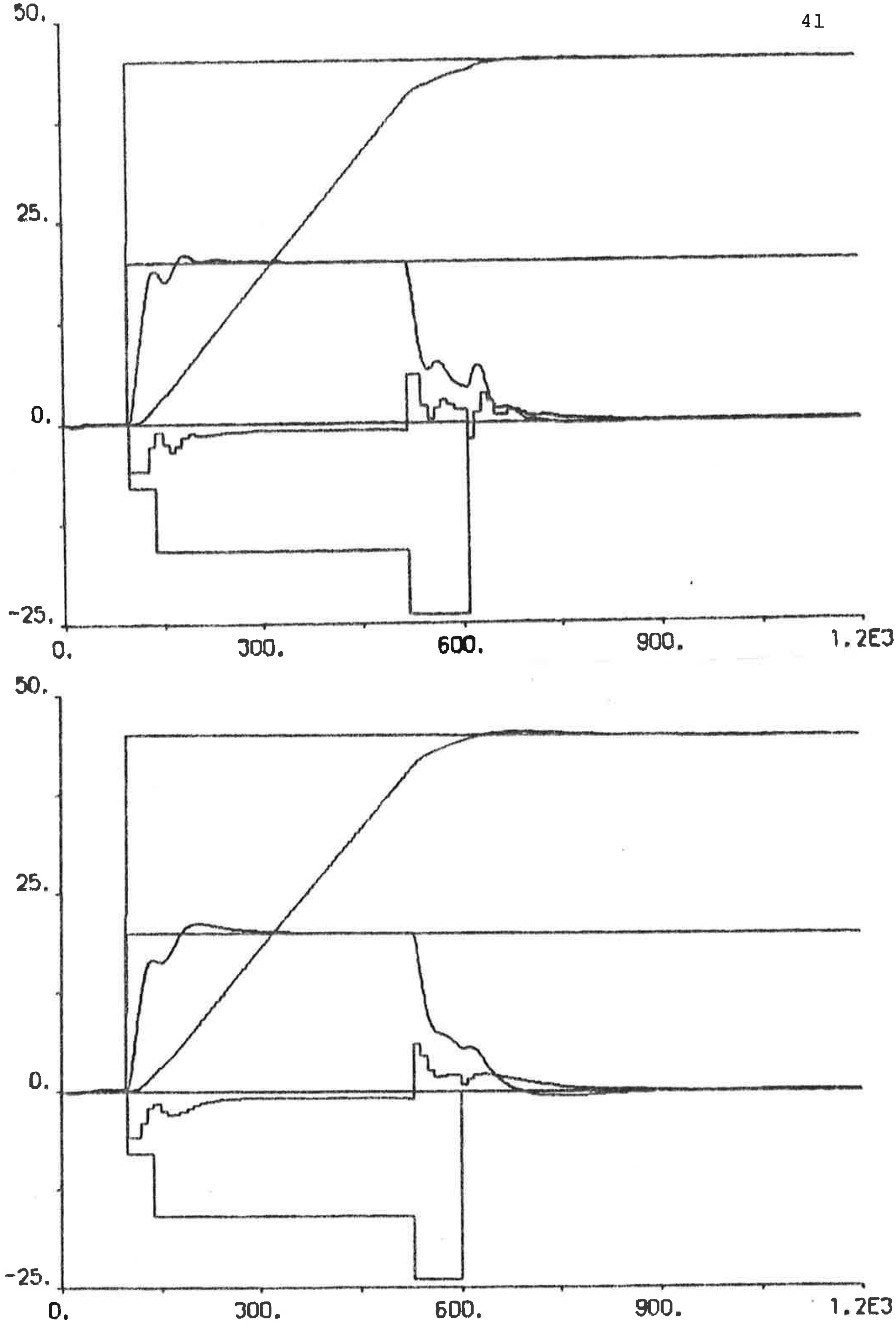


Fig. 5.16 - Constant wind force disturbance: $T = 10.5$ m, $\alpha = 90$ deg, $\Delta\psi_{ref} = 45$ deg, $r_{ref} = 0.1$ deg/s.

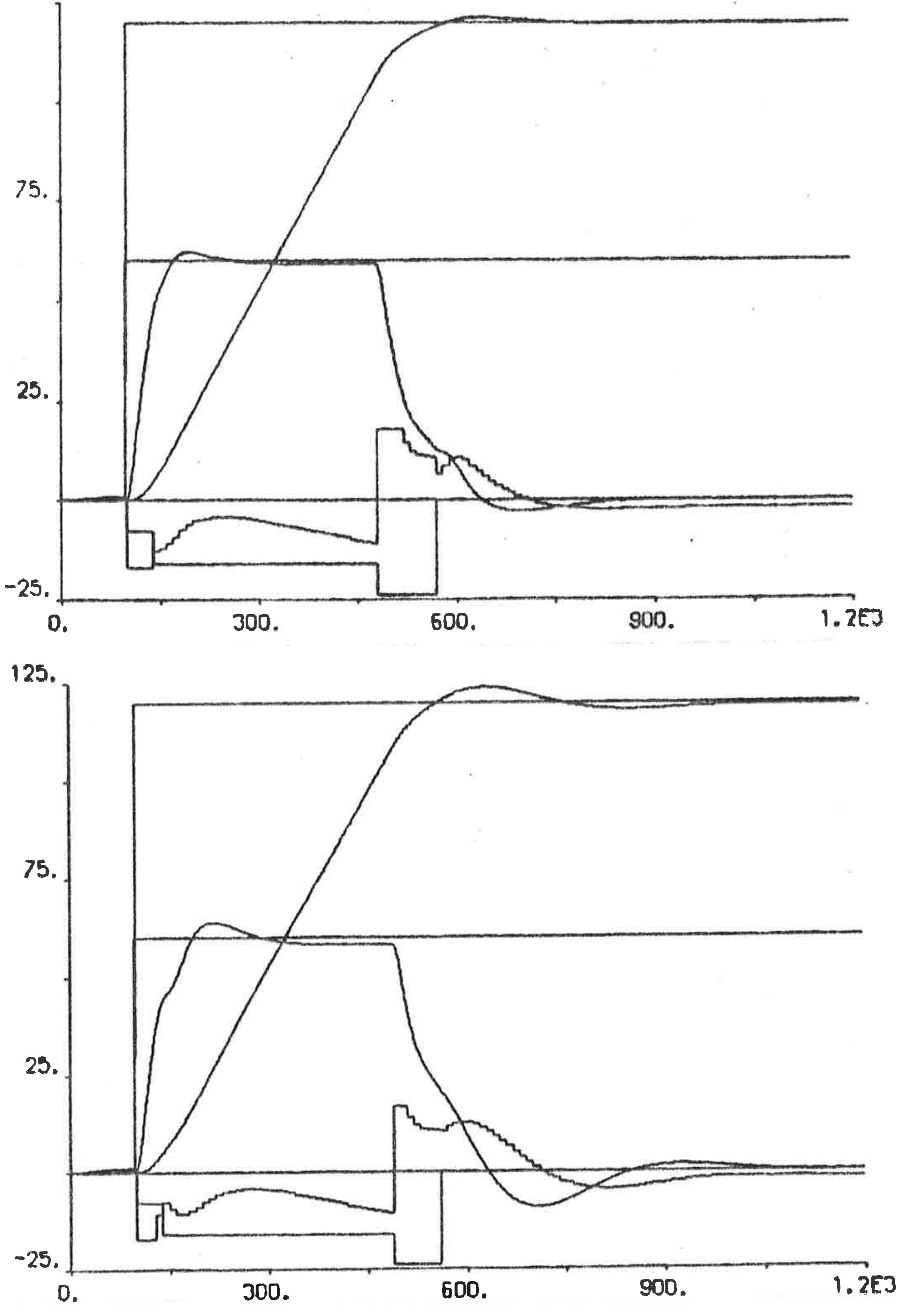


Fig. 5.17 - Constant wind force disturbance: $T = 22.3$ m, $\alpha = 90$ deg, $\Delta\psi_{ref} = 120$ deg, $r_{ref} = 0.3$ deg/s.

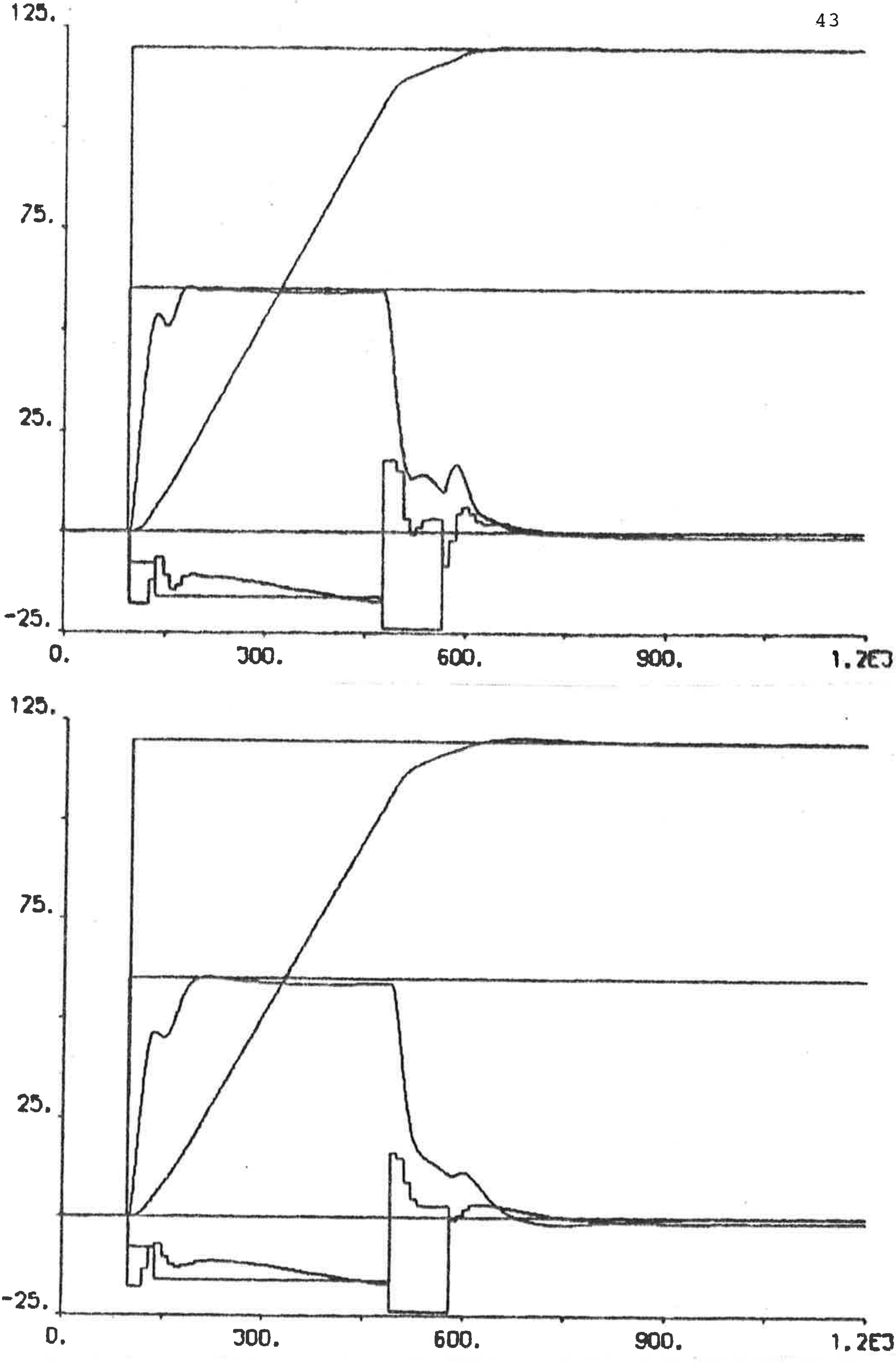


Fig. 5.18 - Constant wind force disturbance: $T = 10.5$ m, $\alpha = 90$ deg, $\Delta\psi_{ref} = 120$ deg, $r_{ref} = 0.3$ deg/s.

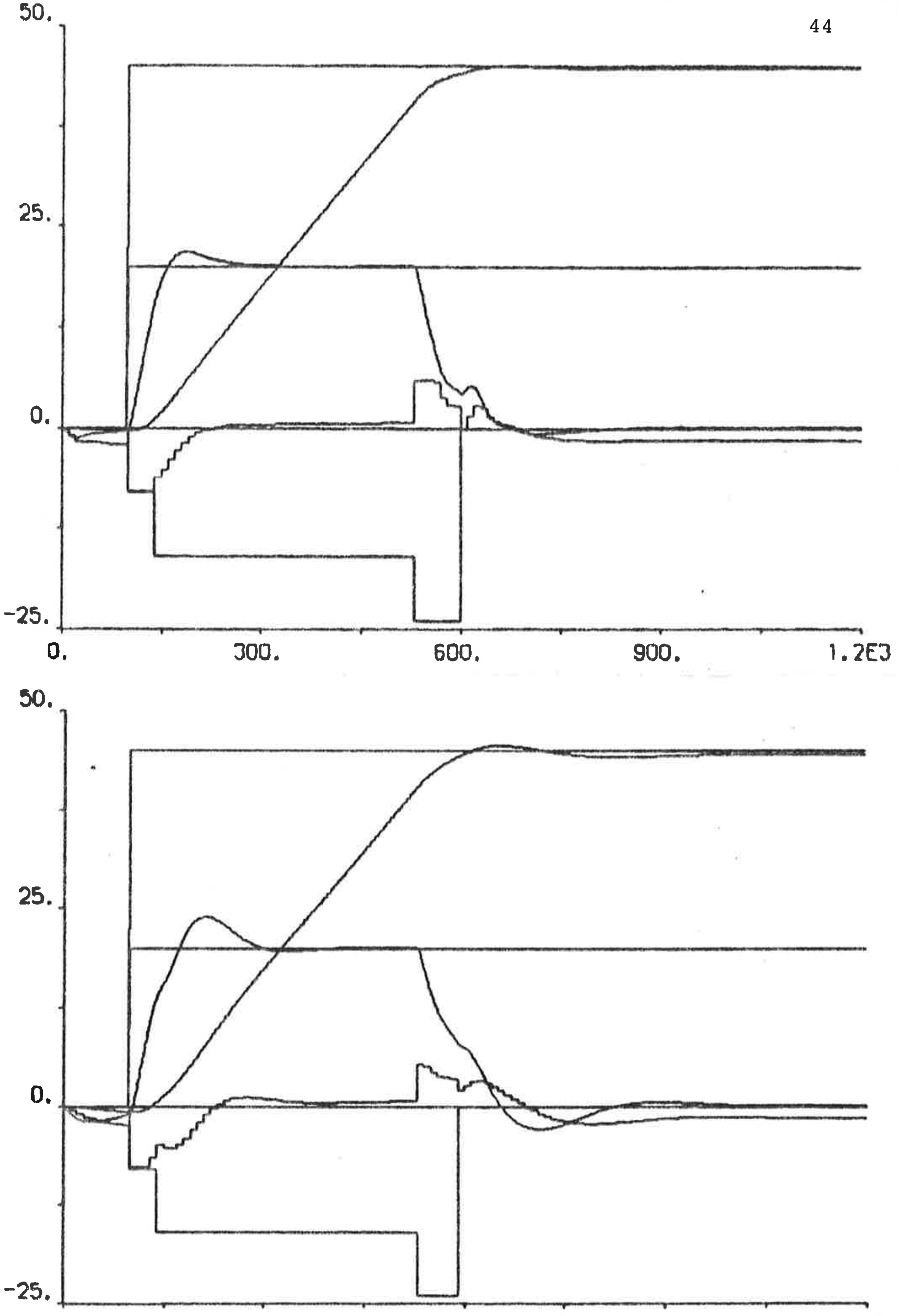


Fig. 5.19 - Constant wind force disturbance: $T = 22.3$ m, $\alpha = 270$ deg, $\Delta\psi_{ref} = 45$ deg, $r_{ref} = 0.1$ deg/s.

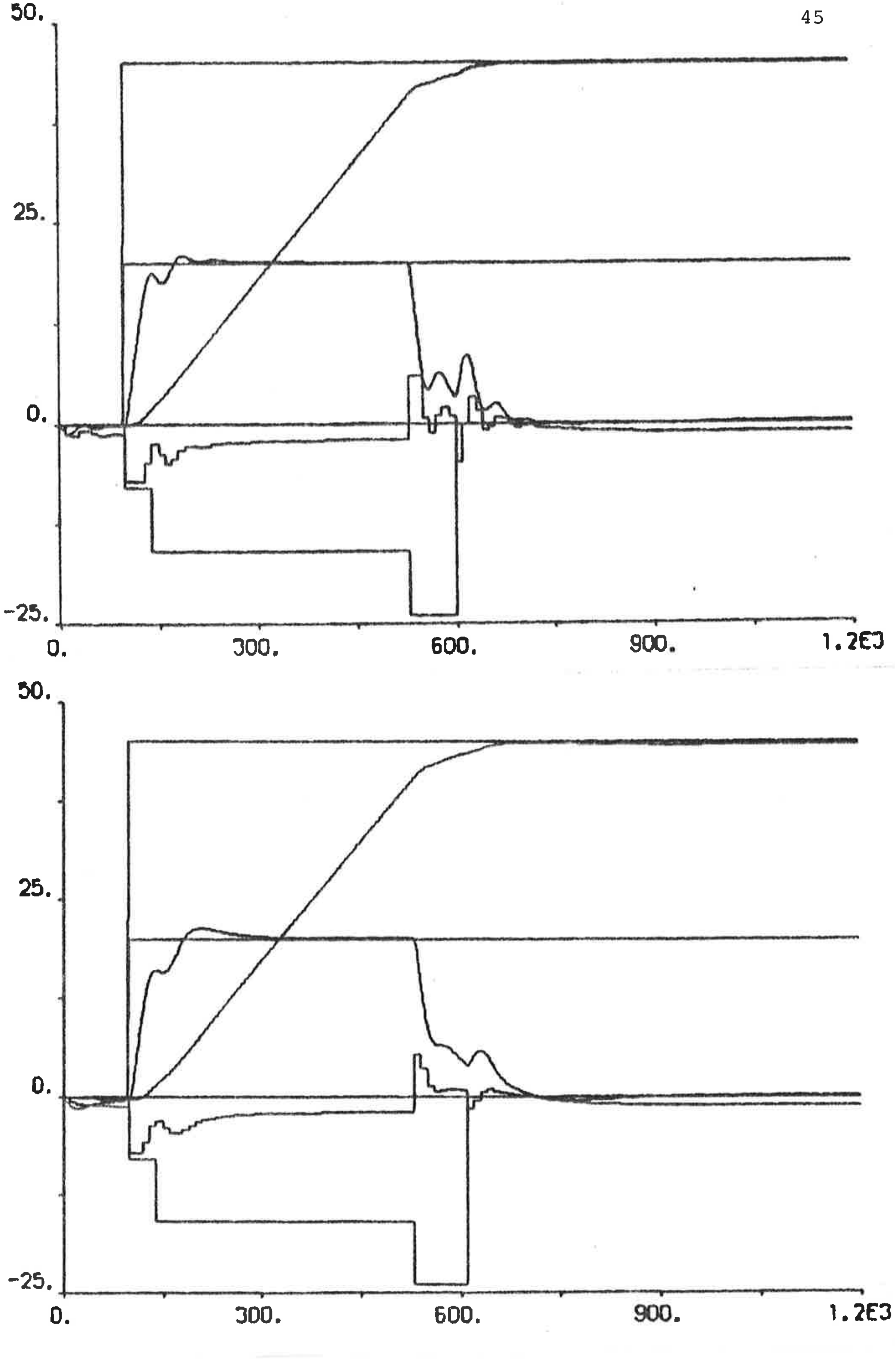


Fig. 5.20 - Constant wind force disturbance: $T = 10.5$ m, $\alpha = 270$ deg, $\Delta\psi_{ref} = 45$ deg, $r_{ref} = 0.1$ deg/s.

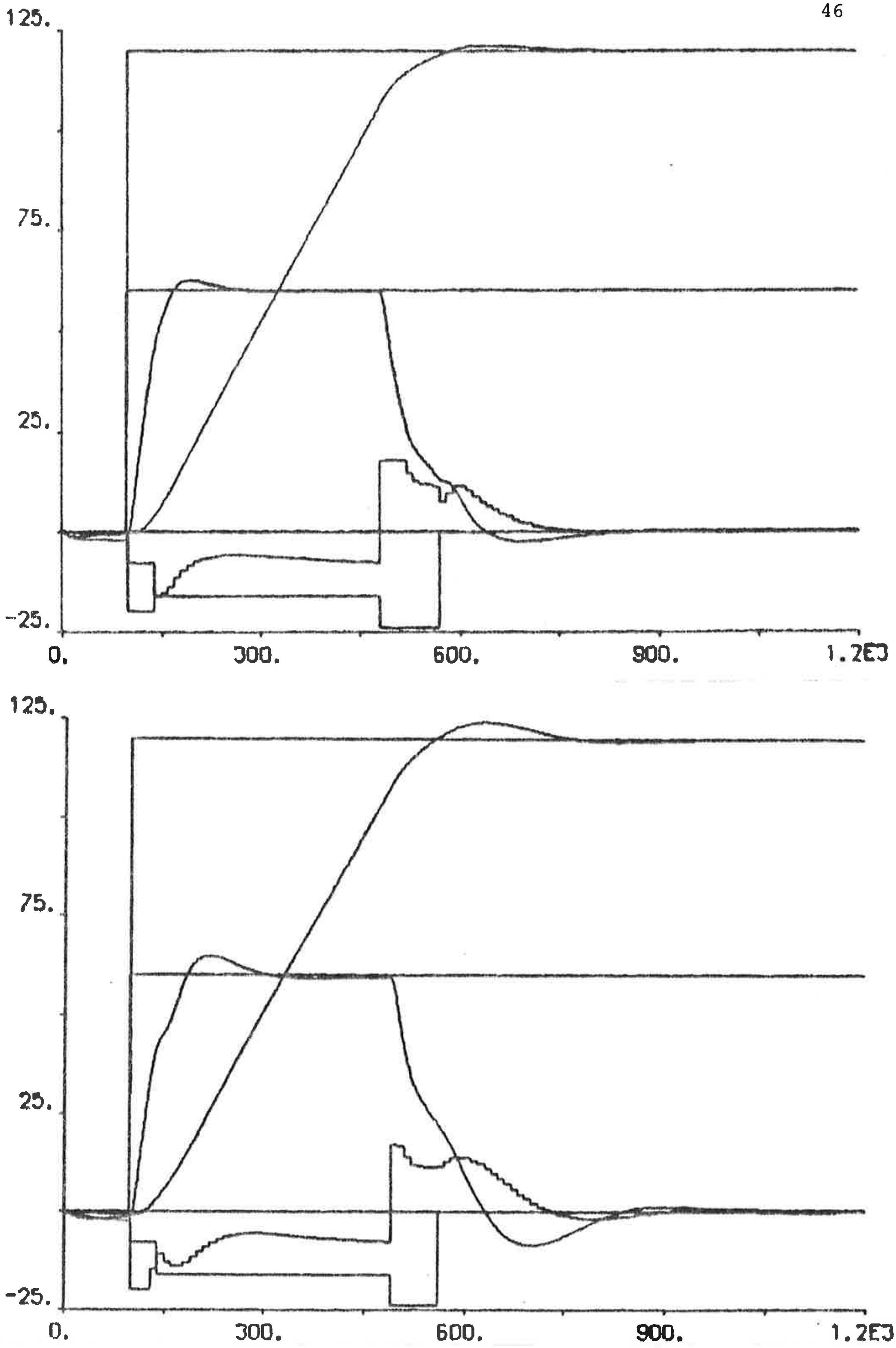


Fig. 5.21 - Constant wind force disturbance: T = 22.3 m, α = 270 deg, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.3 deg/s.

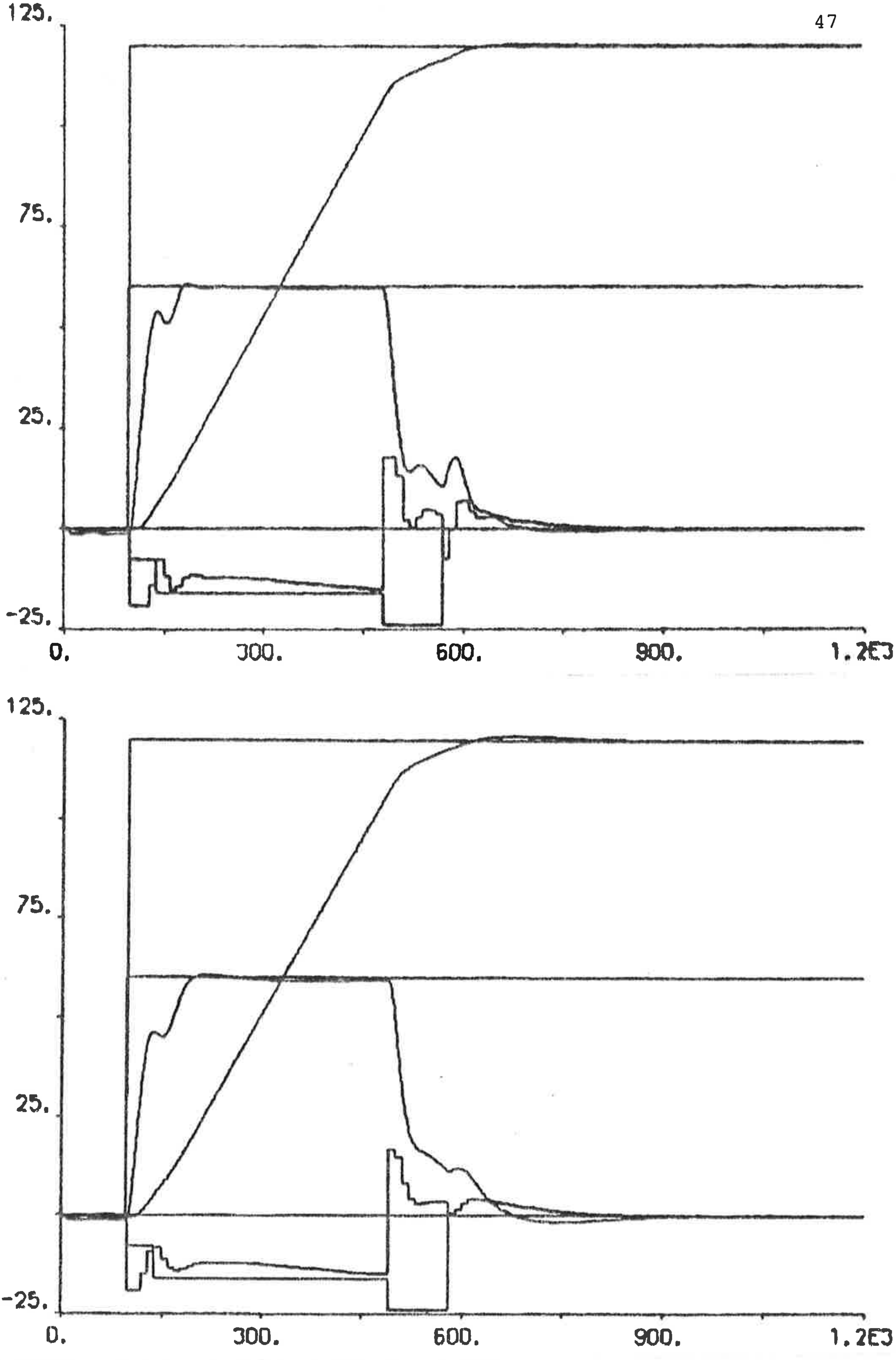


Fig. 5.22 - Constant wind force disturbance: $T = 10.5$ m, $\alpha = 270$ deg, $\Delta\psi_{ref} = 120$ deg, $r_{ref} = 0.3$ deg/s.

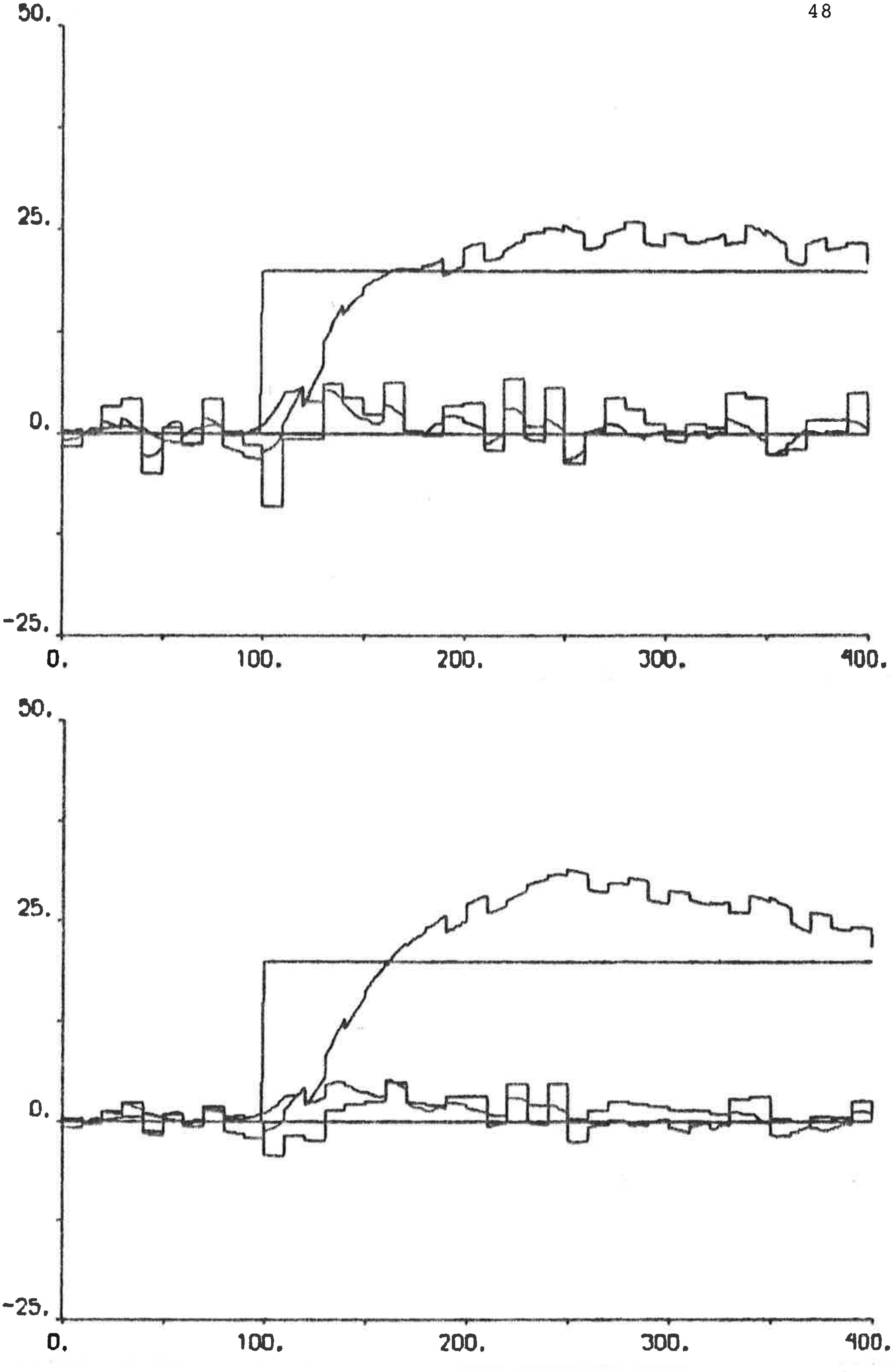


Fig. 5.23 - Stochastic disturbances: T = 22.3 m, α = 90 deg, σ_r = 0.01 deg/s, $\Delta\psi_{ref}$ = 2 deg.

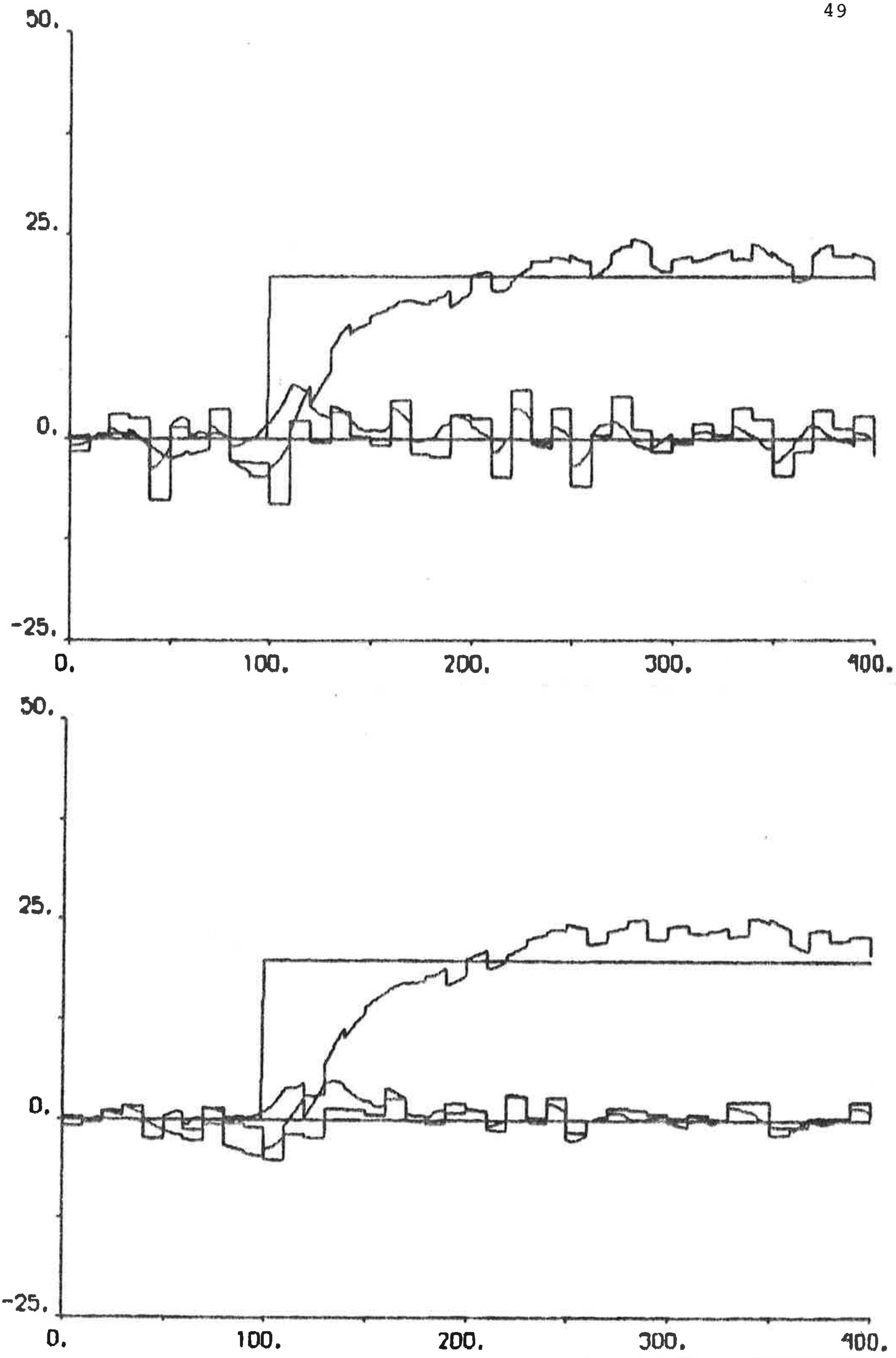


Fig. 5.24 - Stochastic disturbances: $T = 10.5$ m, $\alpha = 90$ deg, $\sigma_r = 0.01$ deg/s, $\Delta\psi_{ref} = 2$ deg.

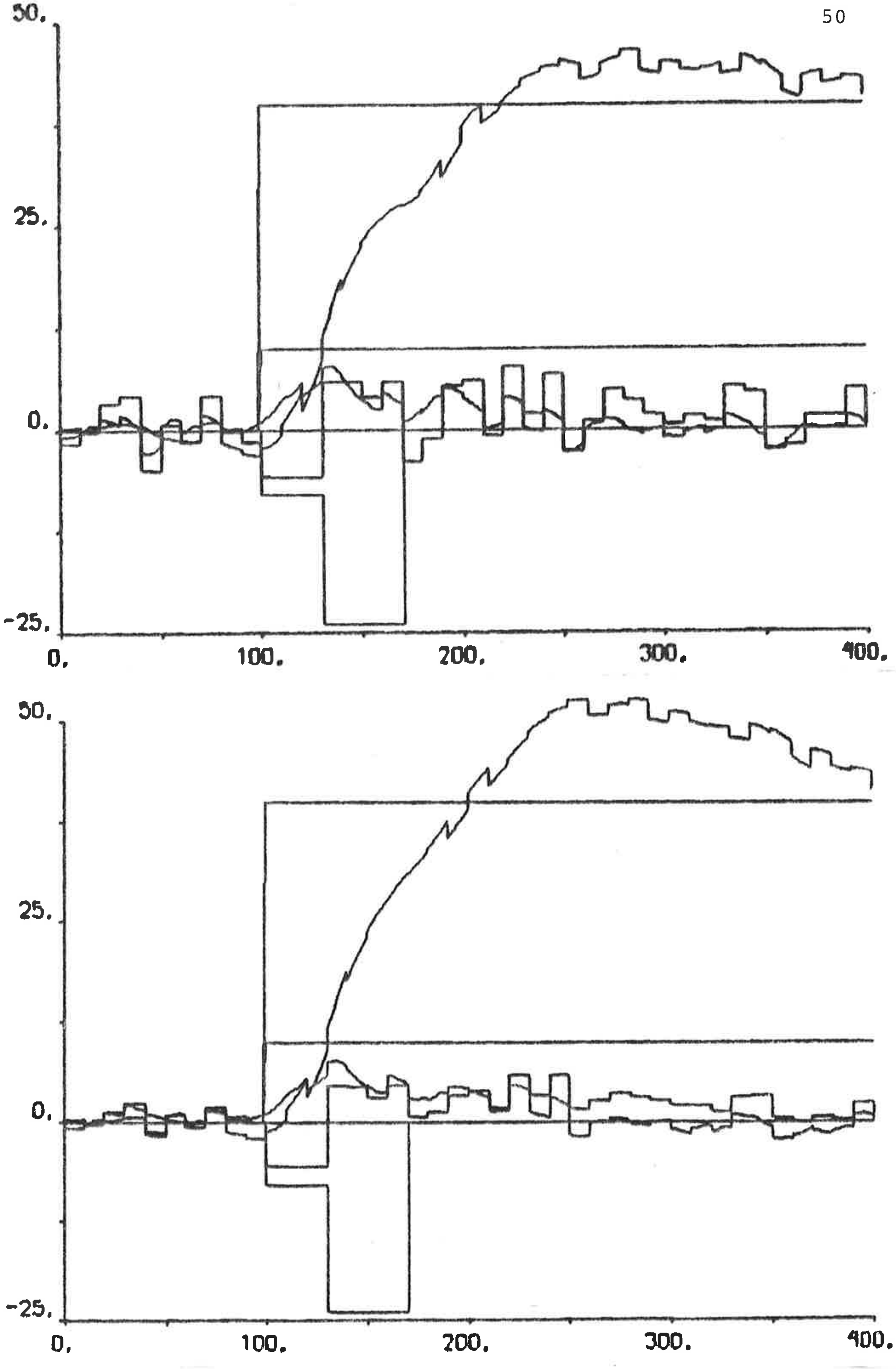
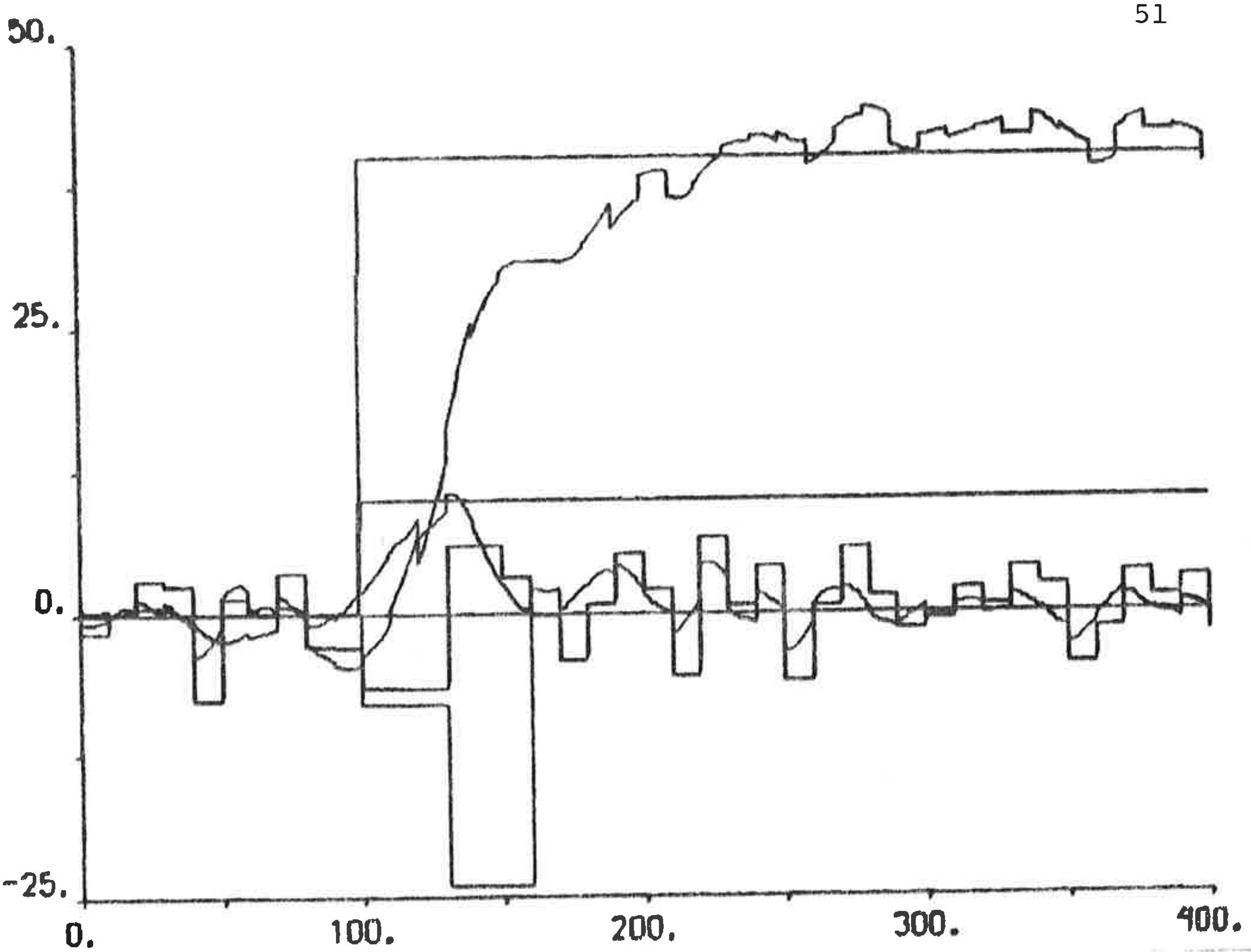


Fig. 5.25 - Stochastic disturbances: T = 22.3 m, α = 90 deg, σ_r = 0.01 deg/s, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s.



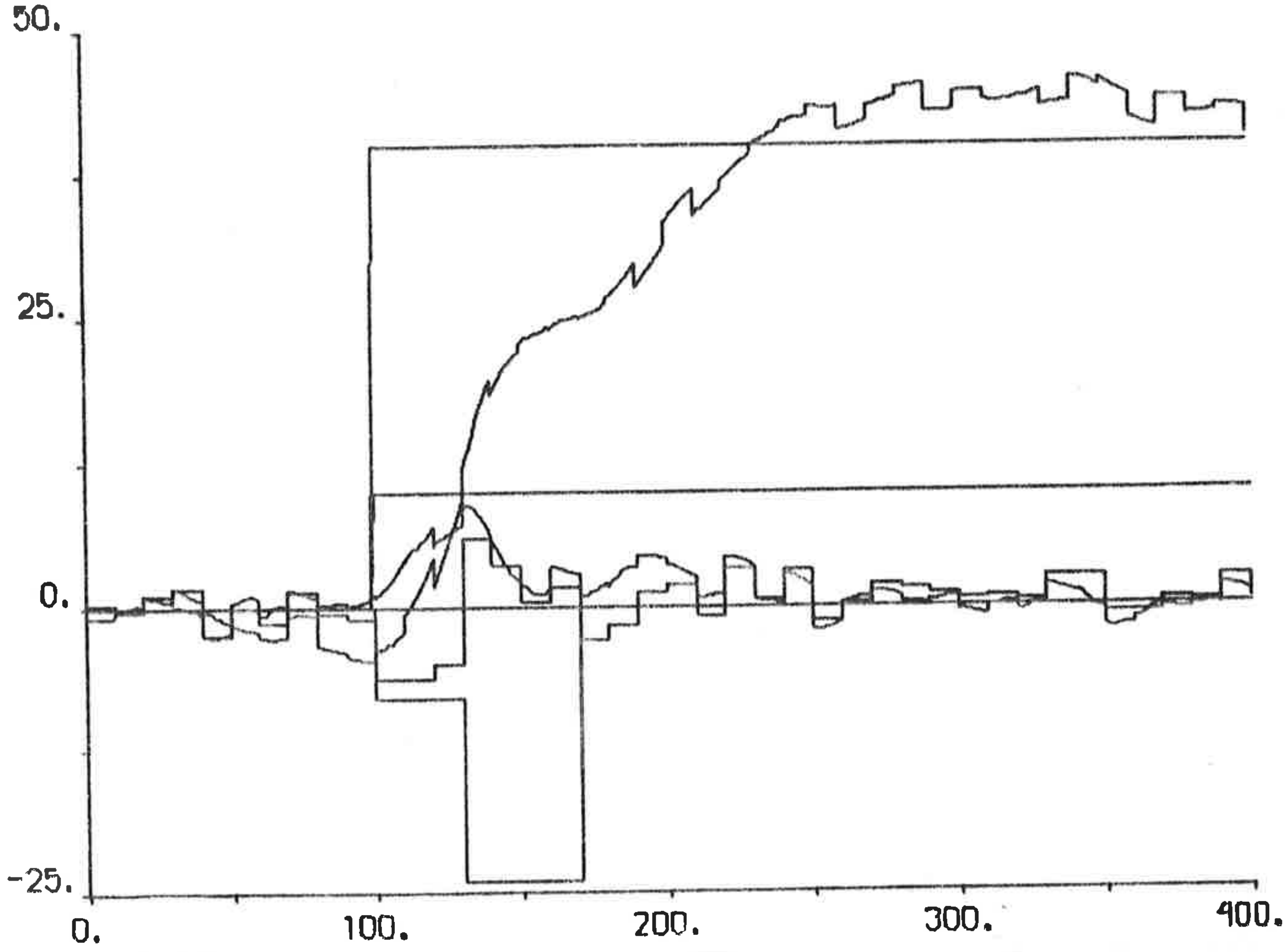


Fig. 5.26 - Stochastic disturbances: T = 10.5 m, α = 90 deg, σ_r = 0.01 deg/s, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s.

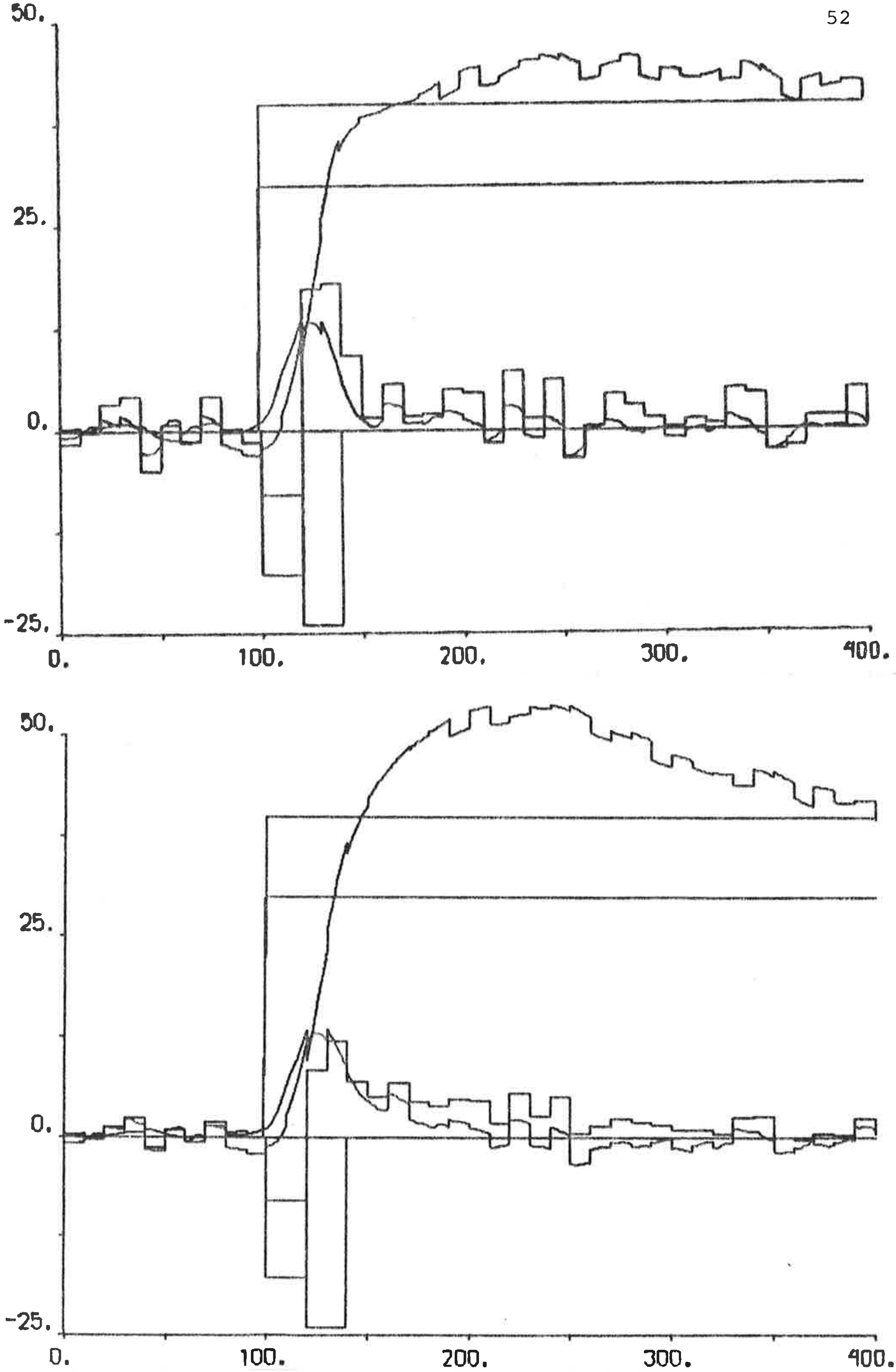


Fig. 5.27 - Stochastic disturbances: $T = 22.3$ m, $\alpha = 90$ deg, $\sigma_r = 0.01$ deg/s, $\Delta\psi_{ref} = 4$ deg, $r_{ref} = 0.3$ deg/s.

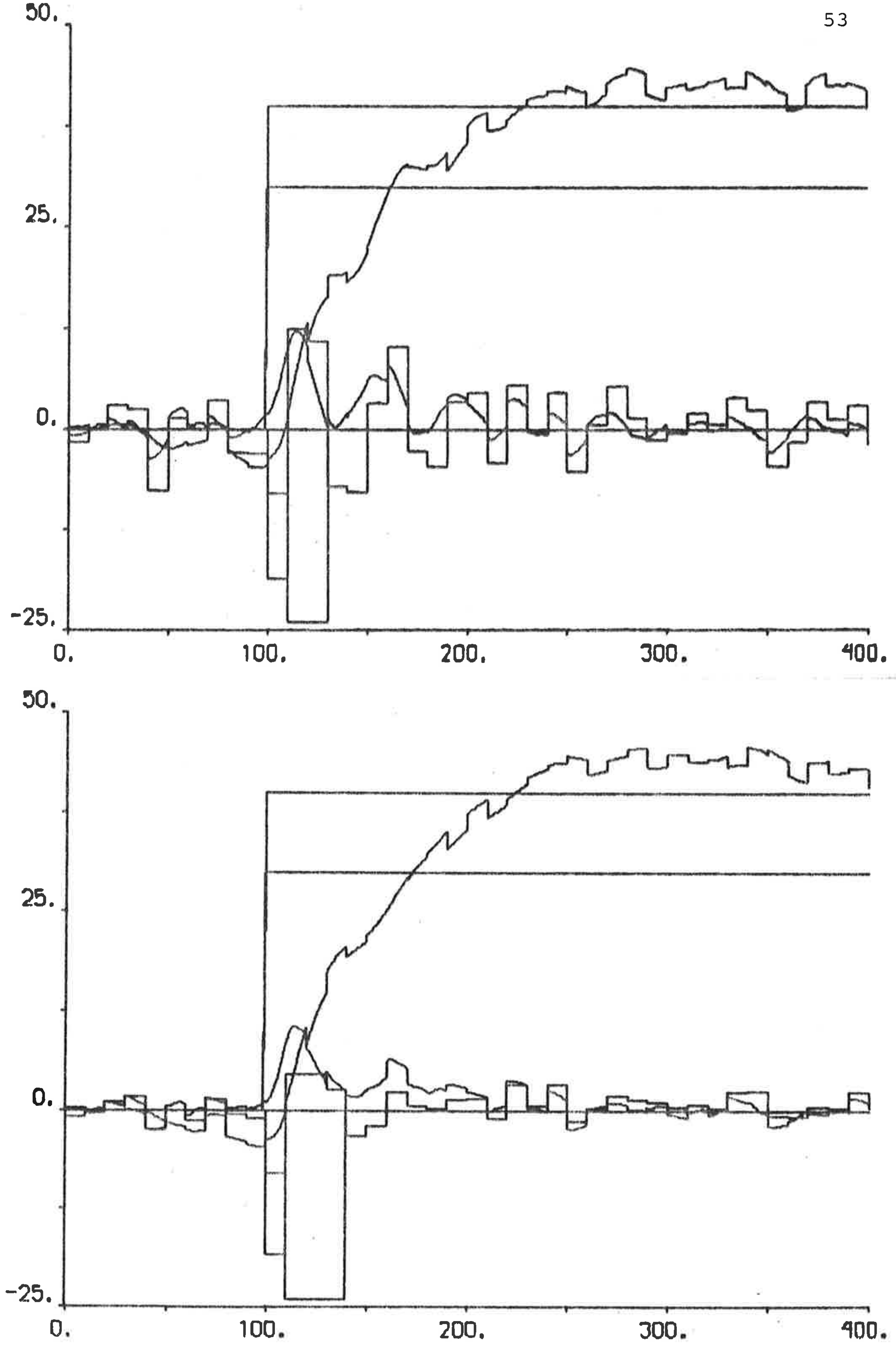
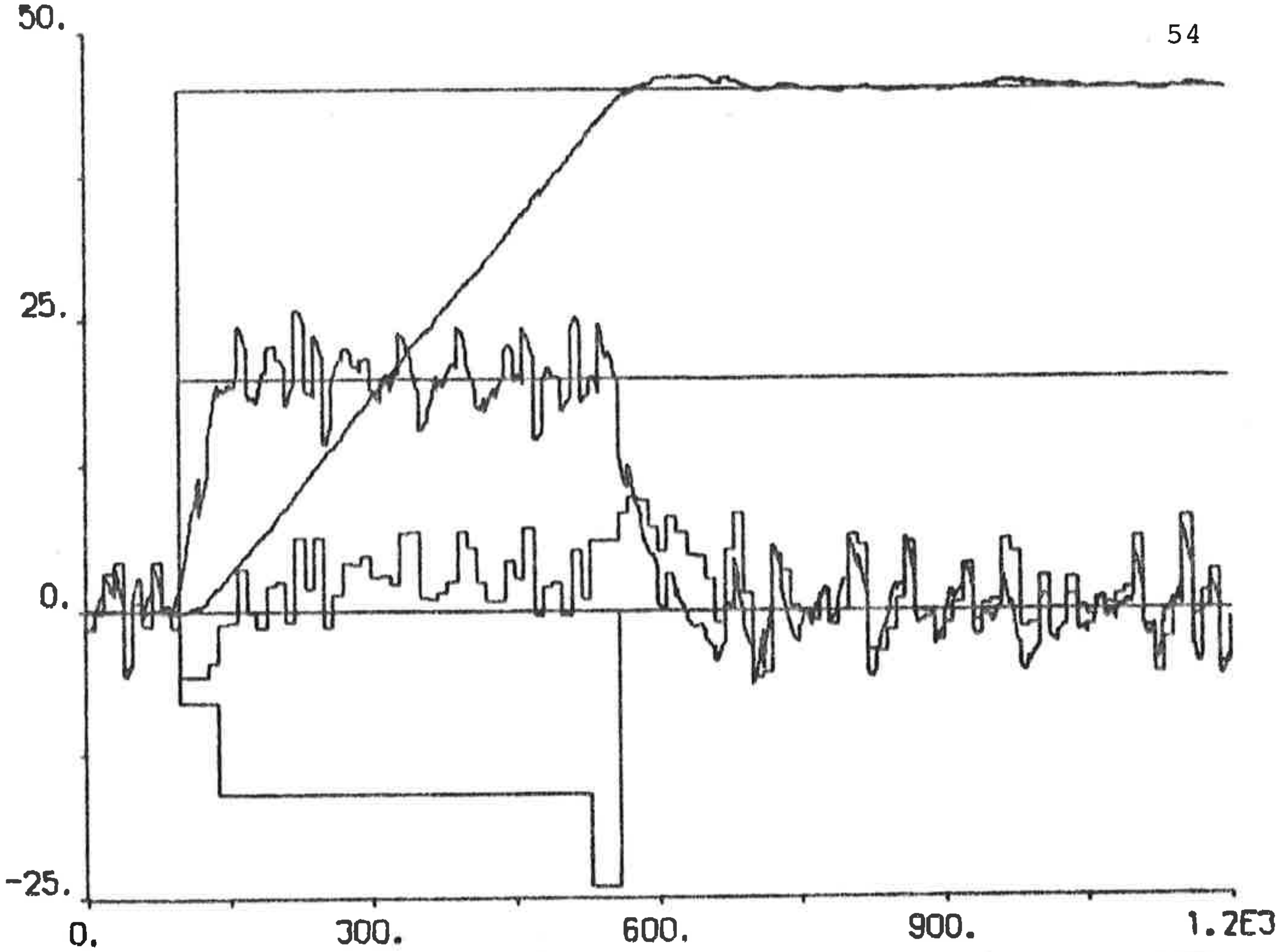


Fig. 5.28 - Stochastic disturbances: $T = 10.5$ m, $\alpha = 90$ deg, $\sigma_r = 0.01$ deg/s, $\Delta\psi_{ref} = 4$ deg, $r_{ref} = 0.3$ deg/s.



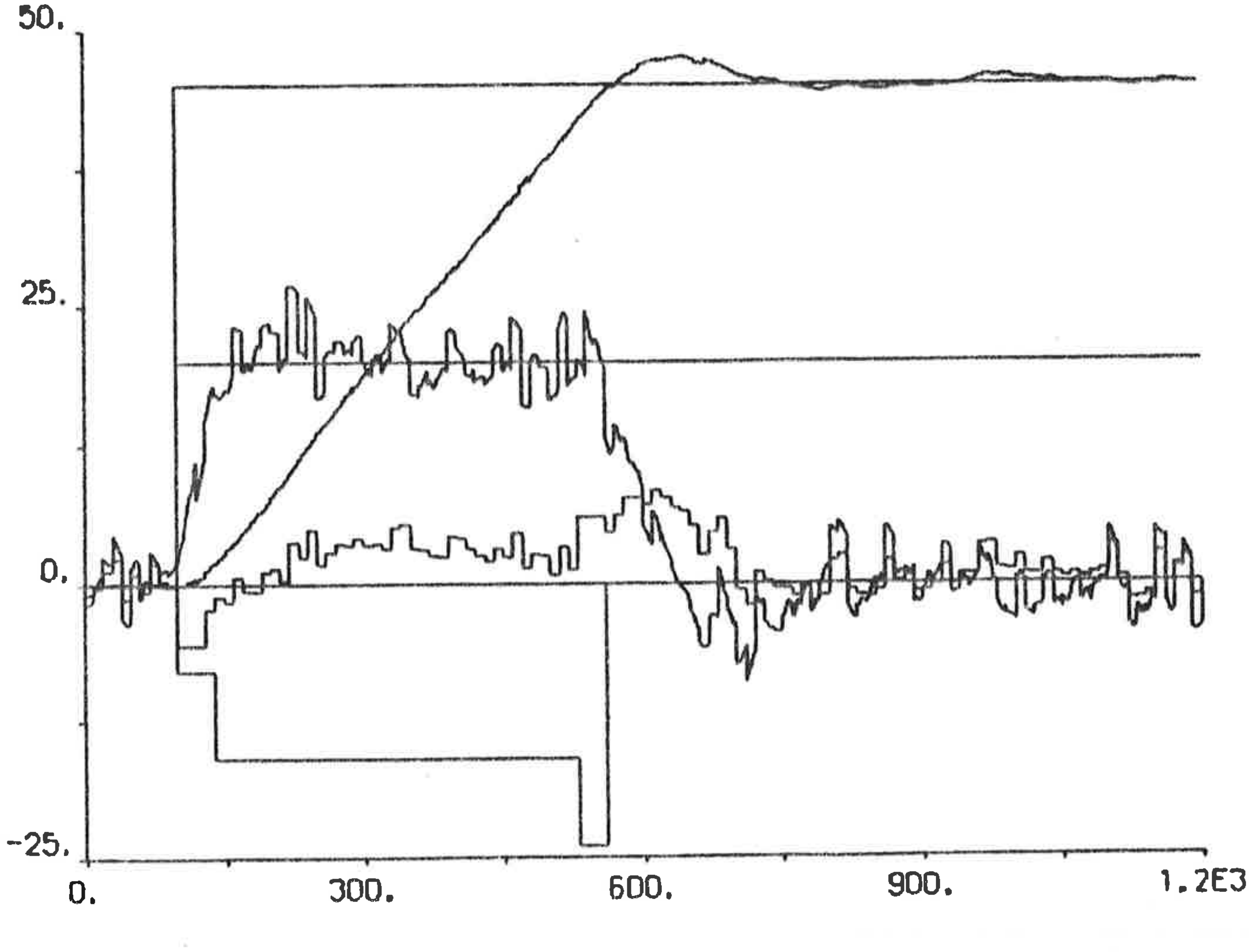


Fig. 5.29 - Stochastic disturbances: $T = 22.3$ m, $\alpha = 90$ deg, $\sigma_r = 0.01$ deg/s, $\Delta\psi_{ref} = 45$ deg, $r_{ref} = 0.1$ deg/s.

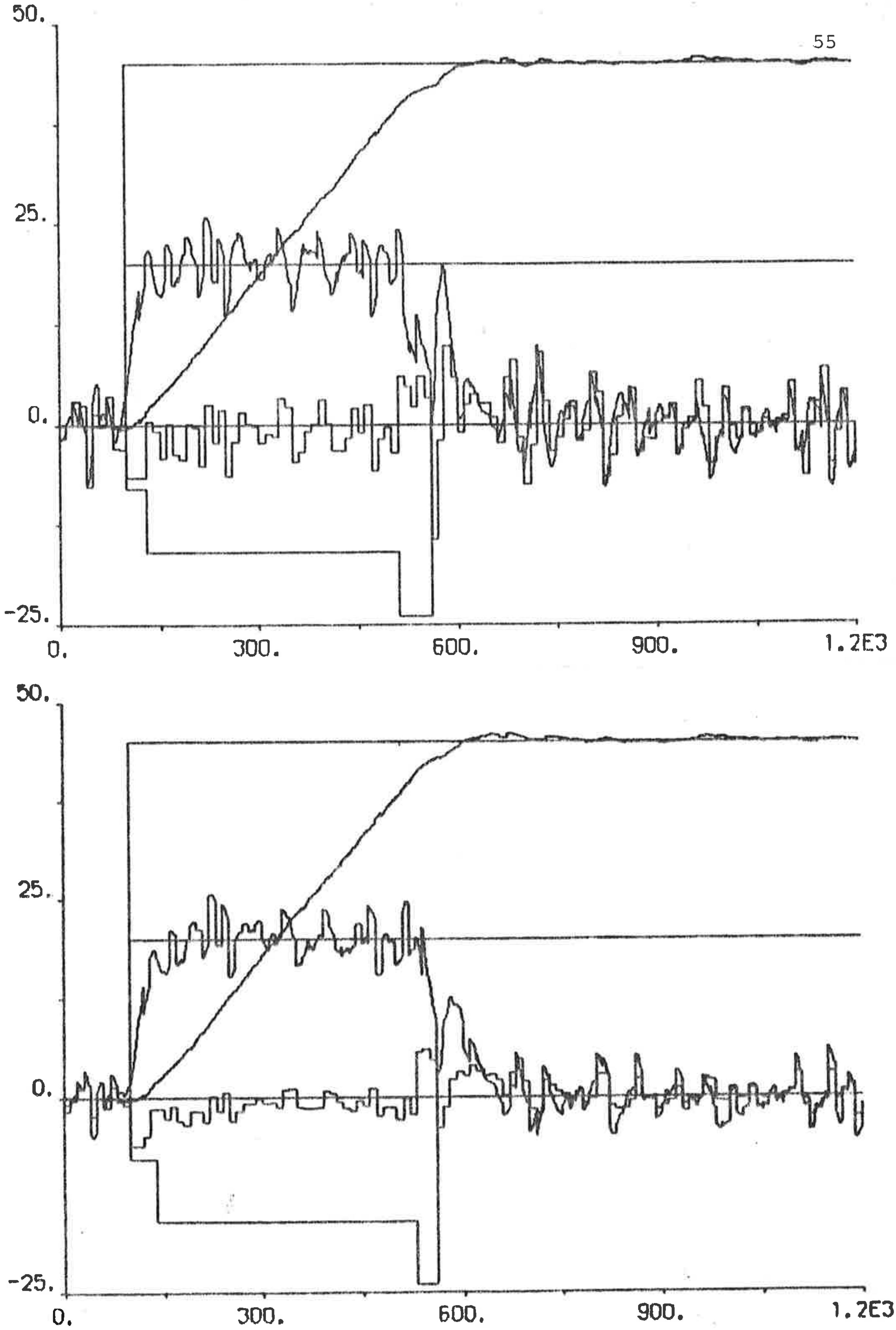


Fig. 5.30 - Stochastic disturbances: T = 10.5 m, α = 90 deg, σ_r = 0.01 deg/s, $\Delta\psi_{ref}$ = 45 deg, r_{ref} = 0.1 deg/s.

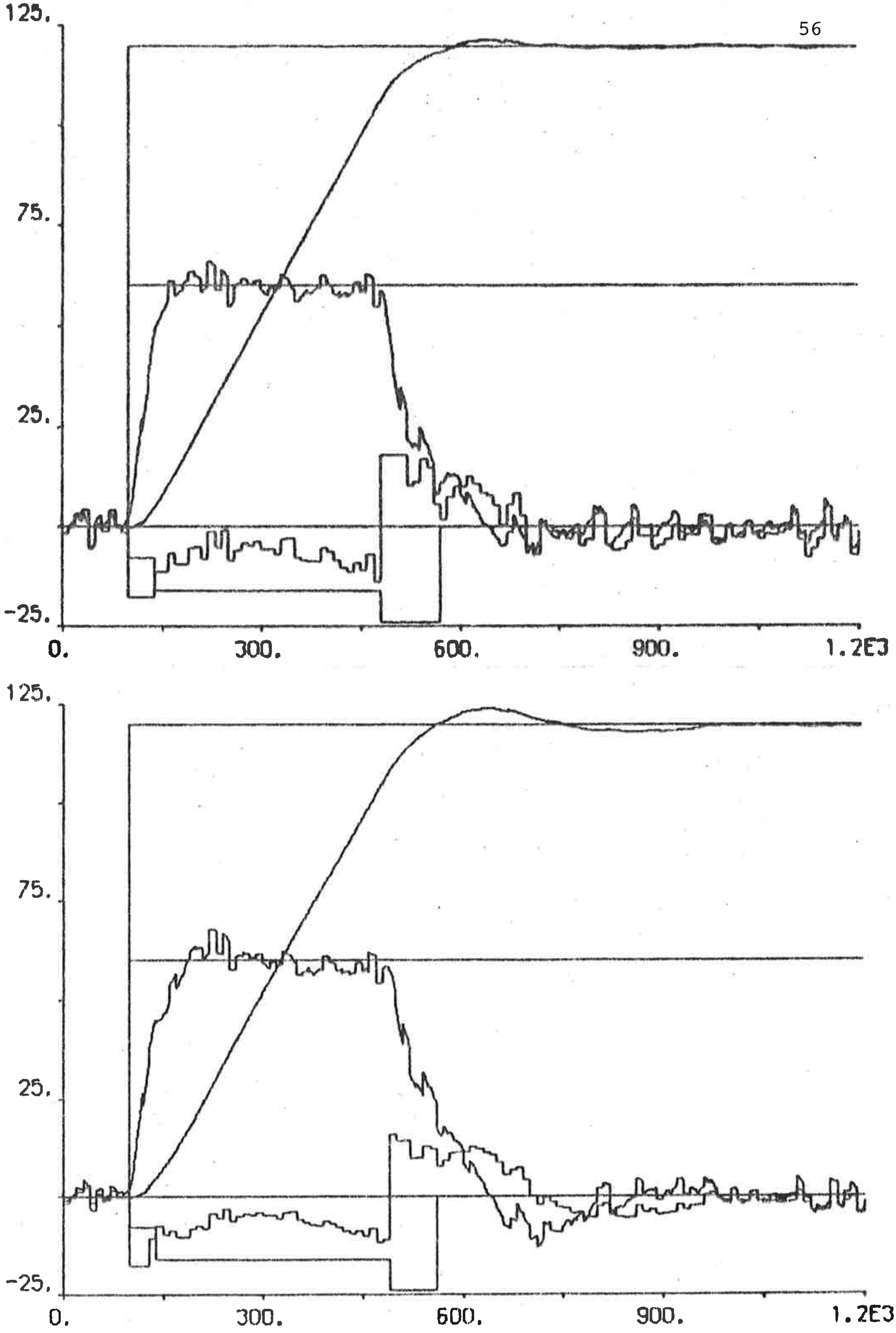


Fig. 5.31 - Stochastic disturbances: $T = 22.3$ m, $\alpha = 90$ deg, $\sigma_r = 0.01$ deg/s, $\Delta\psi_{ref} = 120$ deg, $r_{ref} = 0.3$ deg/s.

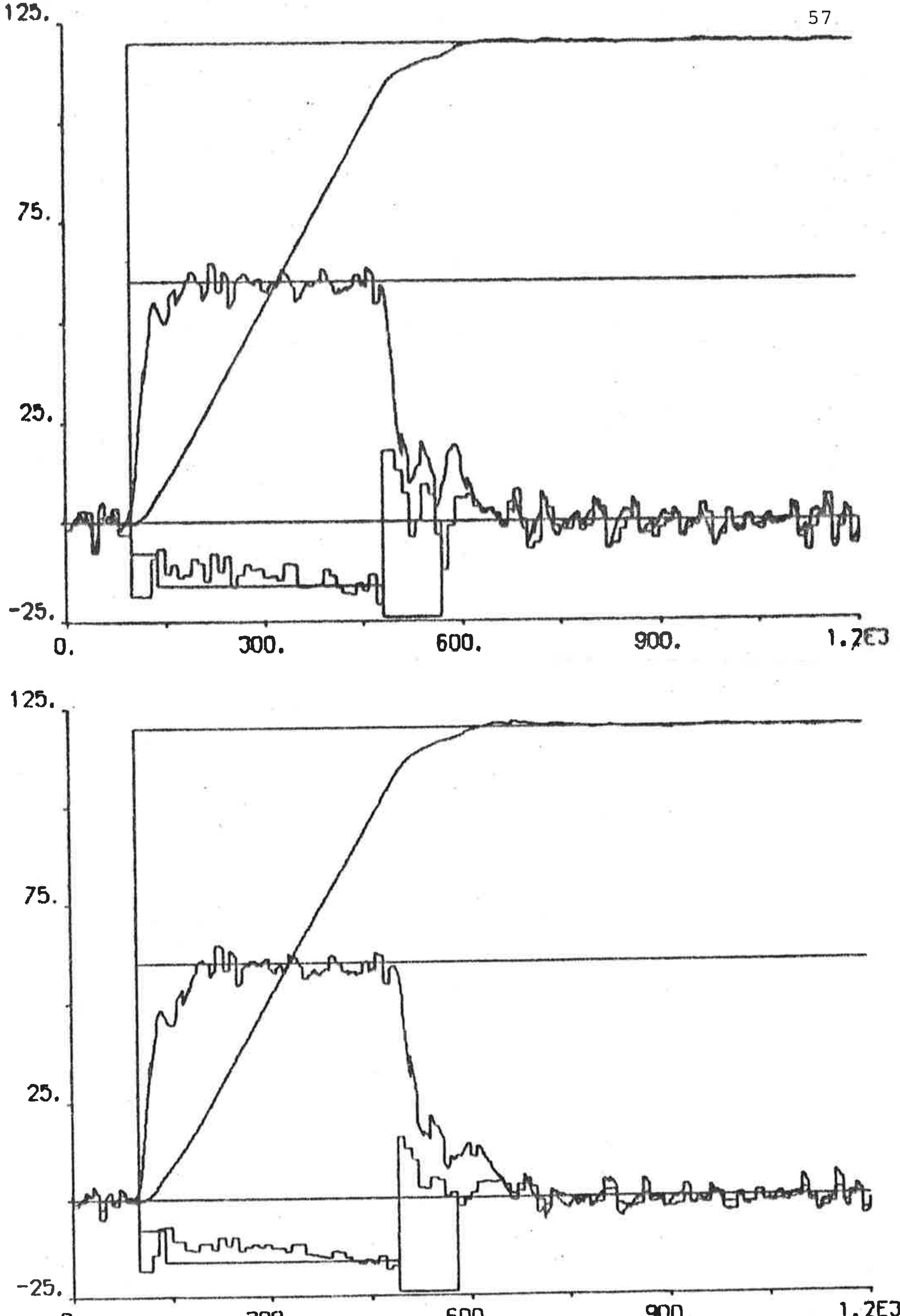
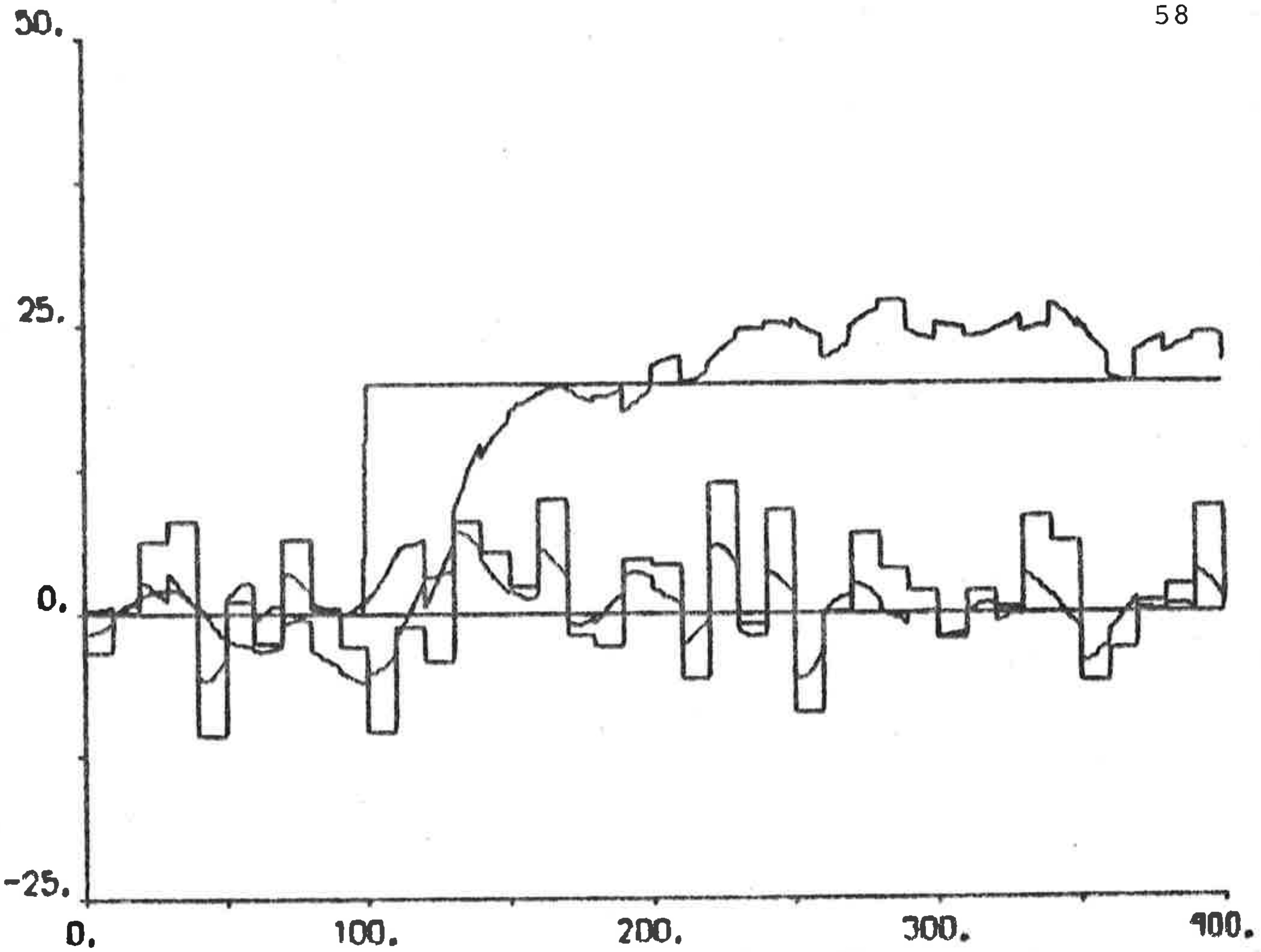


Fig. 5.32 - Stochastic disturbances: T = 10.5 m, α = 90 deg, σ_r = 0.01 deg/s, $\Delta\psi_{ref}$ = 120 deg, r_{ref} = 0.3 deg/s.



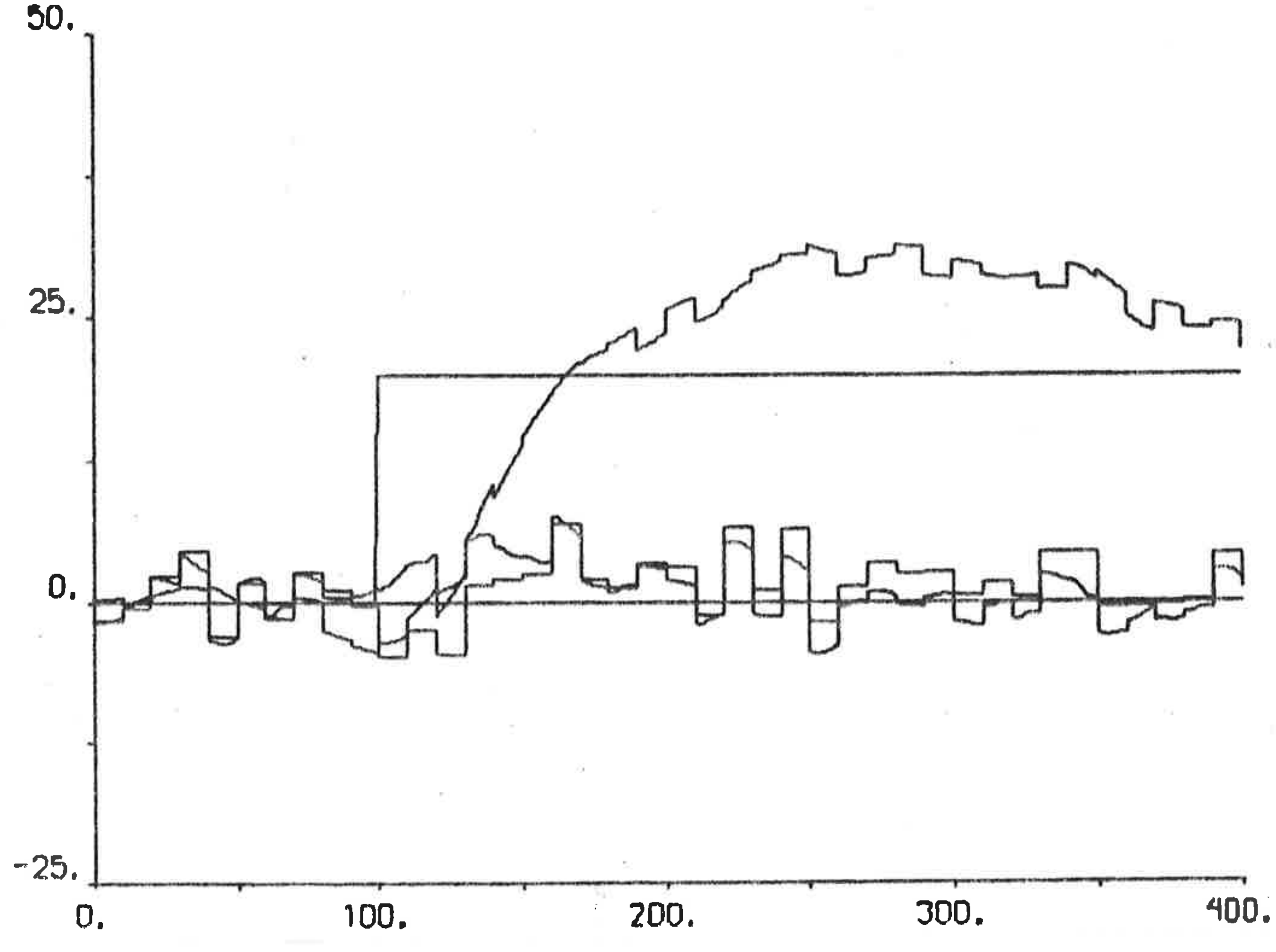


Fig. 5.33 - Stochastic disturbances: T = 22.3 m, α = 90 deg, σ_r = 0.02 deg/s, $\Delta\psi_{ref}$ = 2 deg.

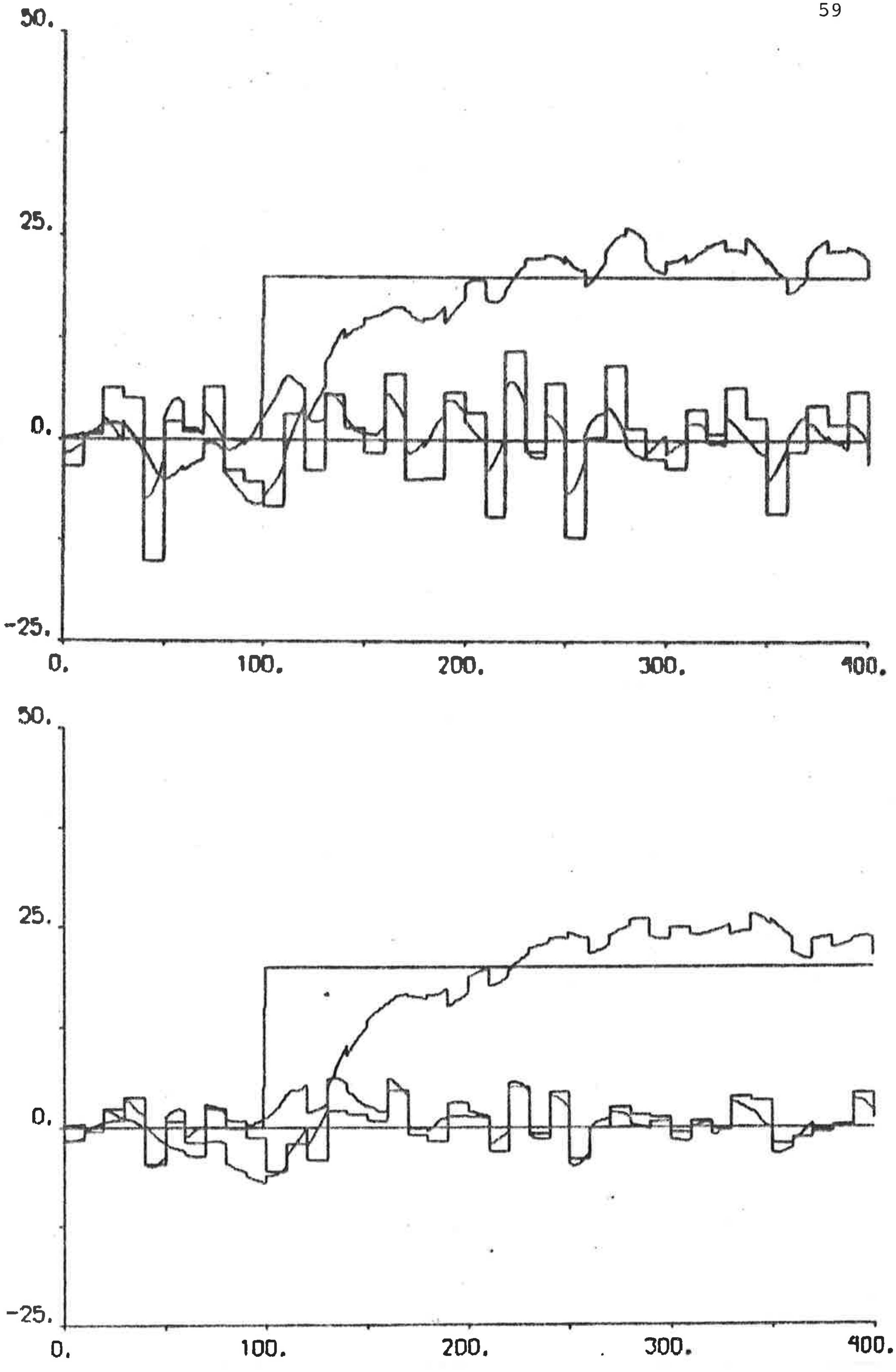
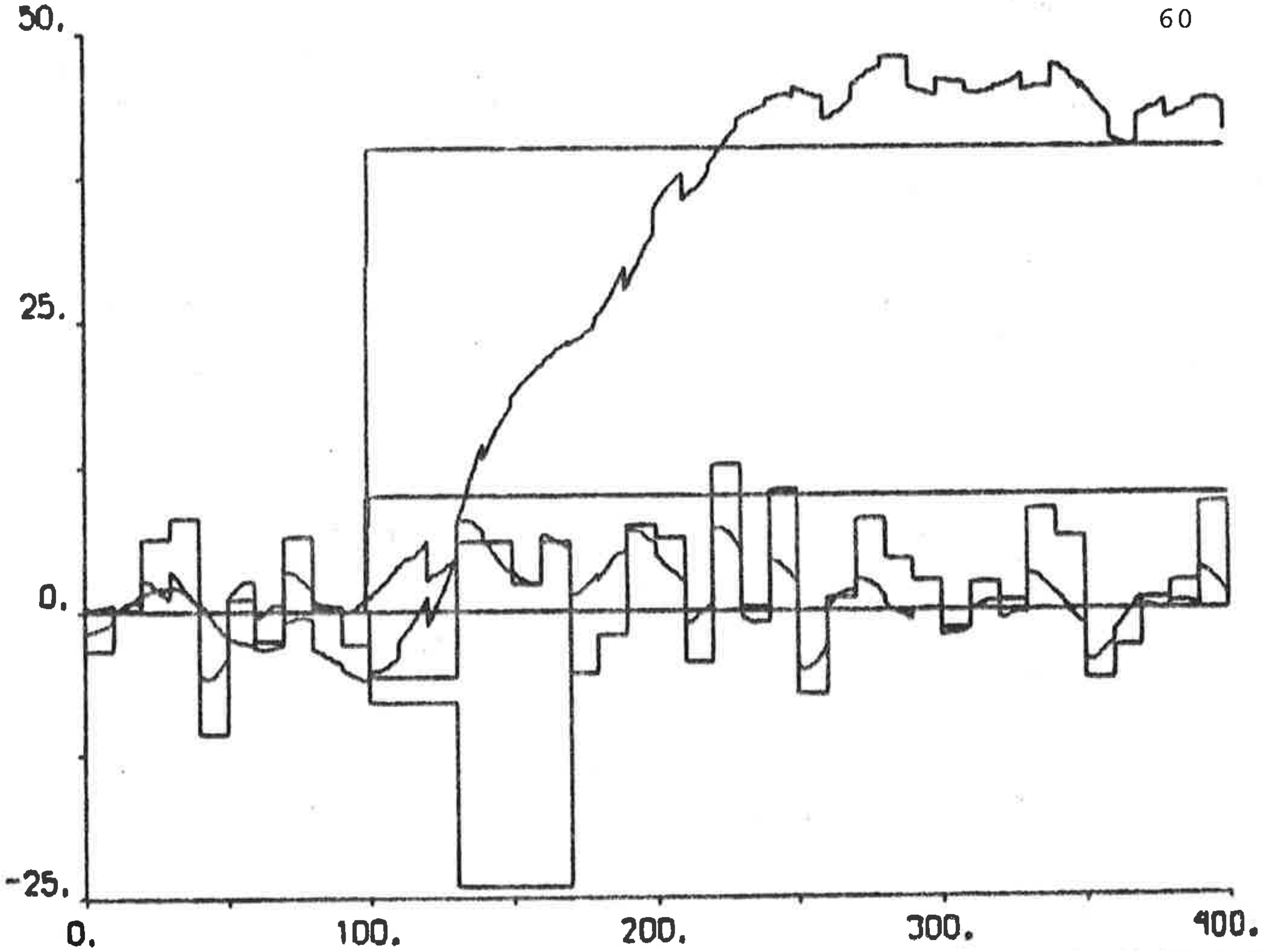


Fig. 5.34 - Stochastic disturbances: T = 10.5 m, α = 90 deg, σ_r = 0.02 deg/s, $\Delta\psi_{ref}$ = 2 deg.



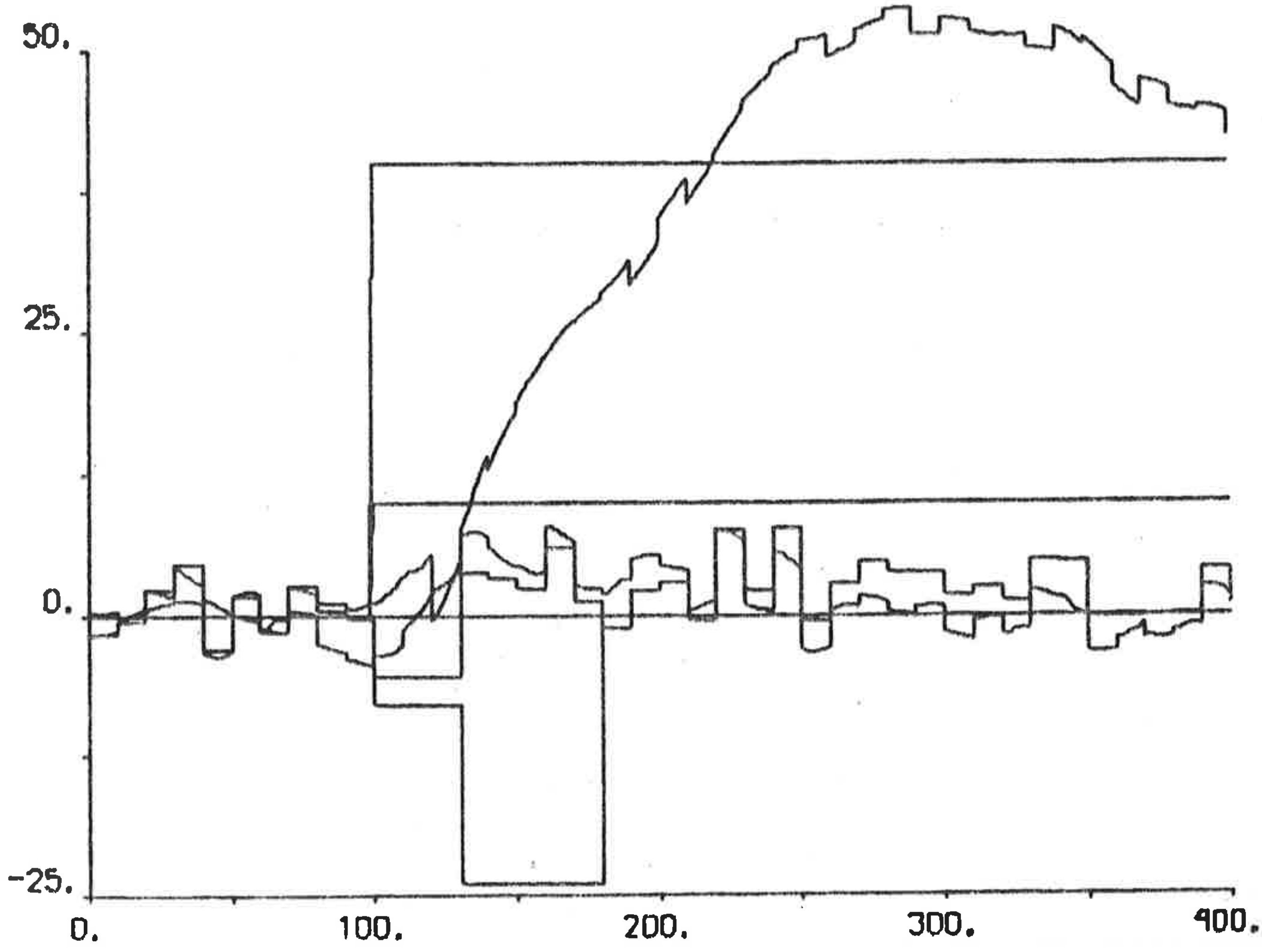


Fig. 5.35 - Stochastic disturbances: T = 22.3 m, α = 90 deg, σ_r = 0.02 deg/s, $\Delta\psi_{ref}$ = 4 deg, r_{ref} = 0.1 deg/s.

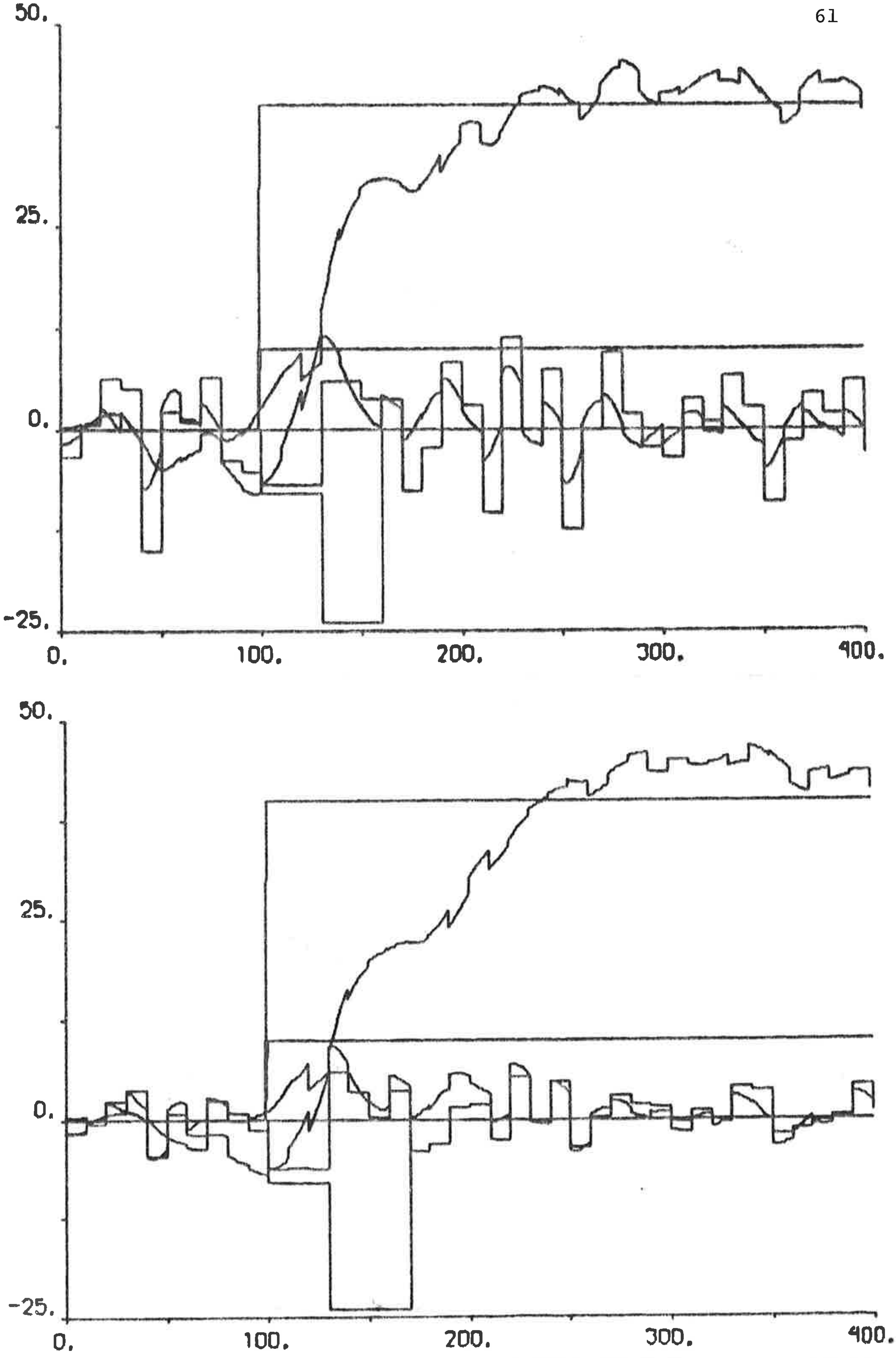
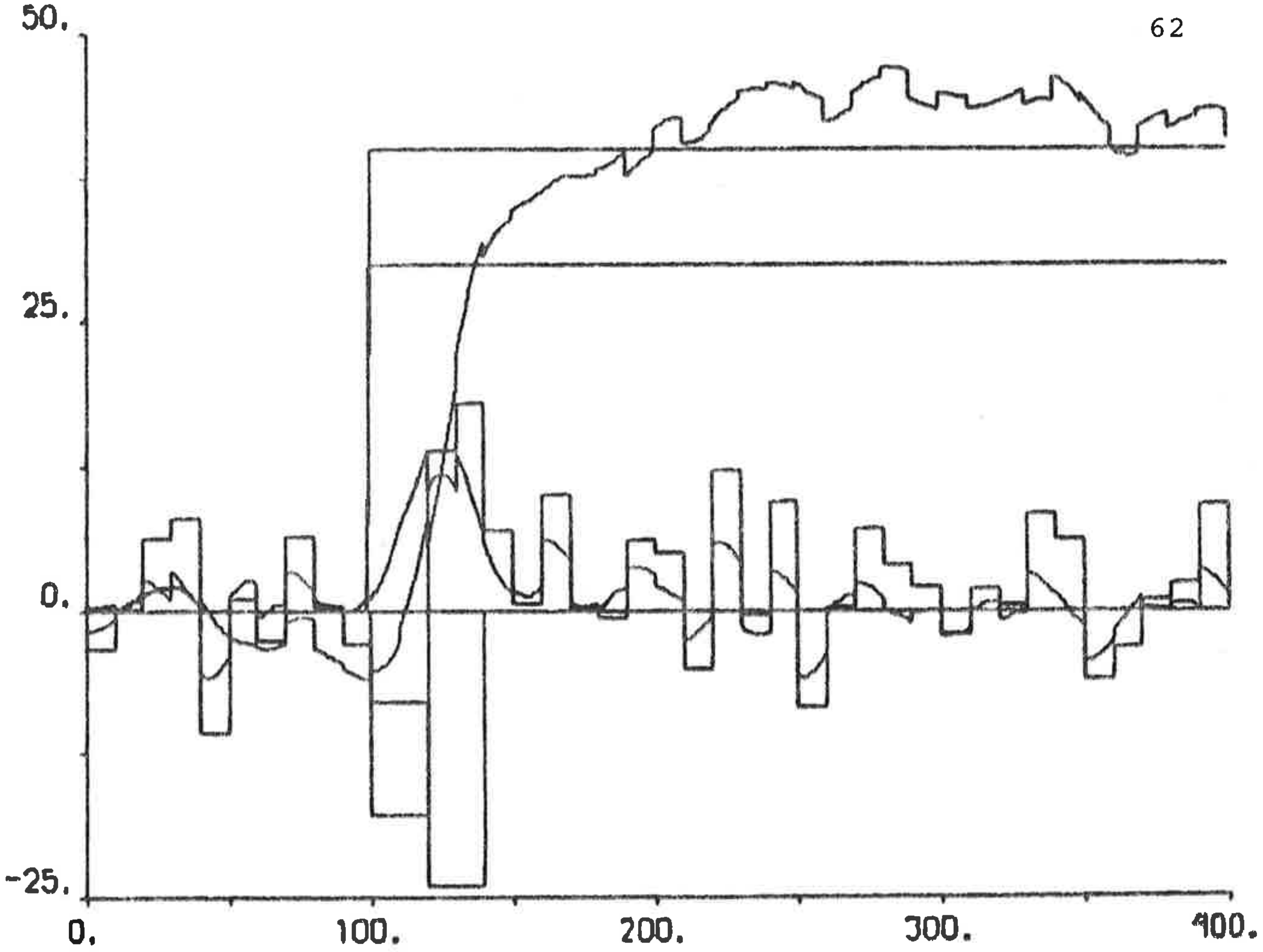


Fig. 5.36 - Stochastic disturbances: $T = 10.5$ m, $\alpha = 90$ deg, $\sigma_r = 0.02$ deg/s, $\Delta\psi_{ref} = 4$ deg, $r_{ref} = 0.1$ deg/s.



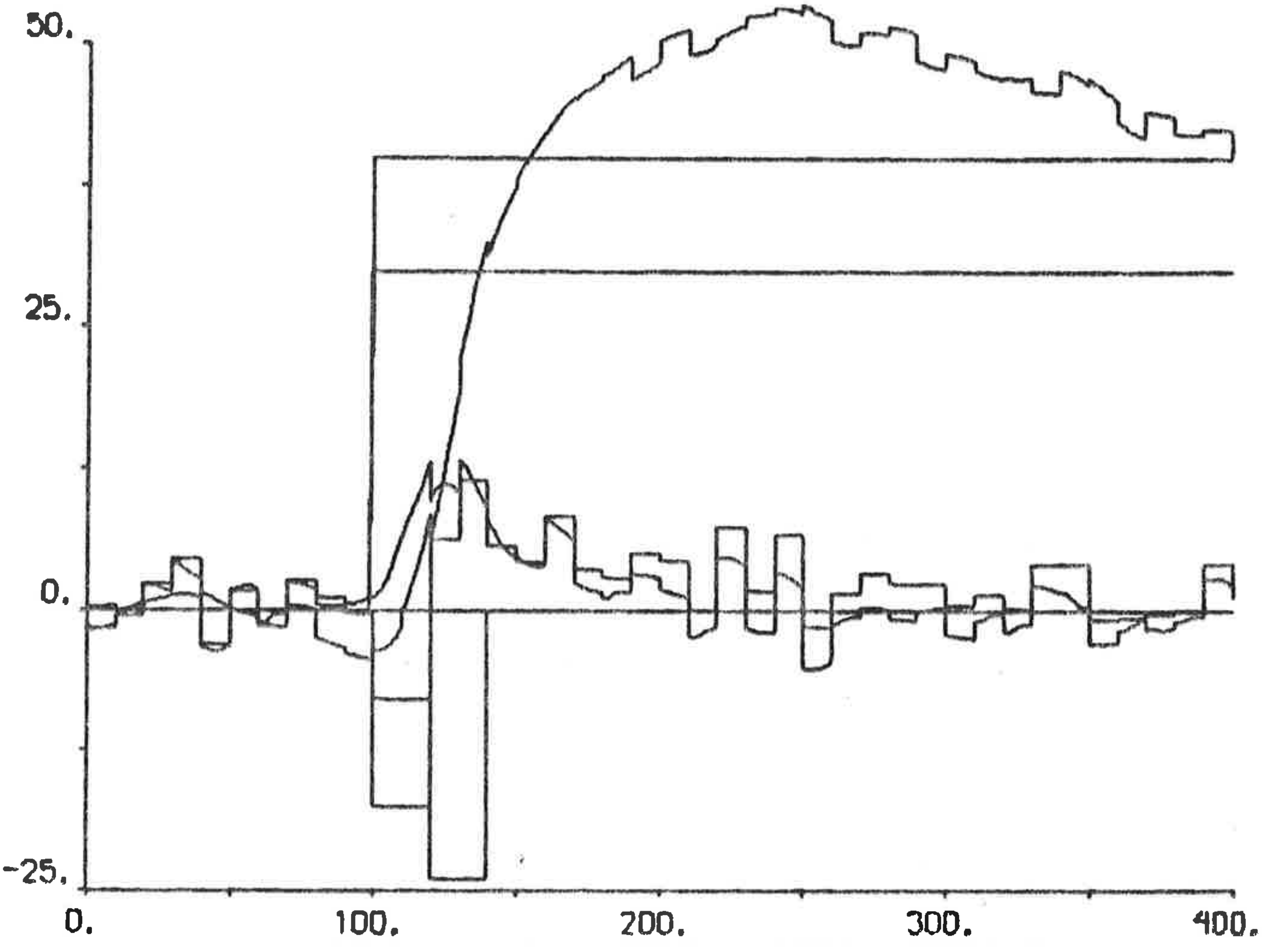
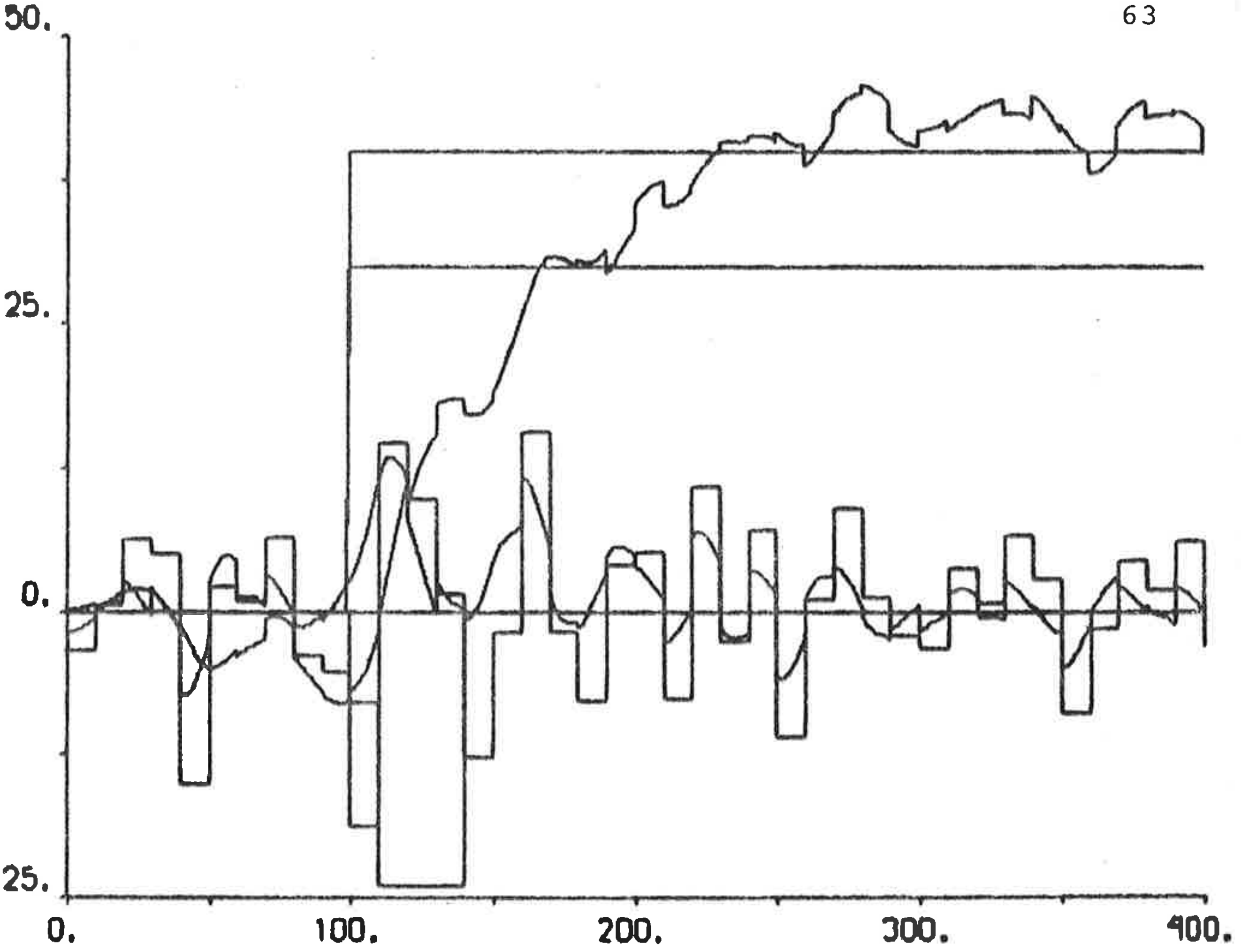


Fig. 5.37 - Stochastic disturbances: $T = 22.3$ m, $\alpha = 90$ deg, $\sigma_r = 0.02$ deg/s, $\Delta\psi_{ref} = 4$ deg, $r_{ref} = 0.3$ deg/s.



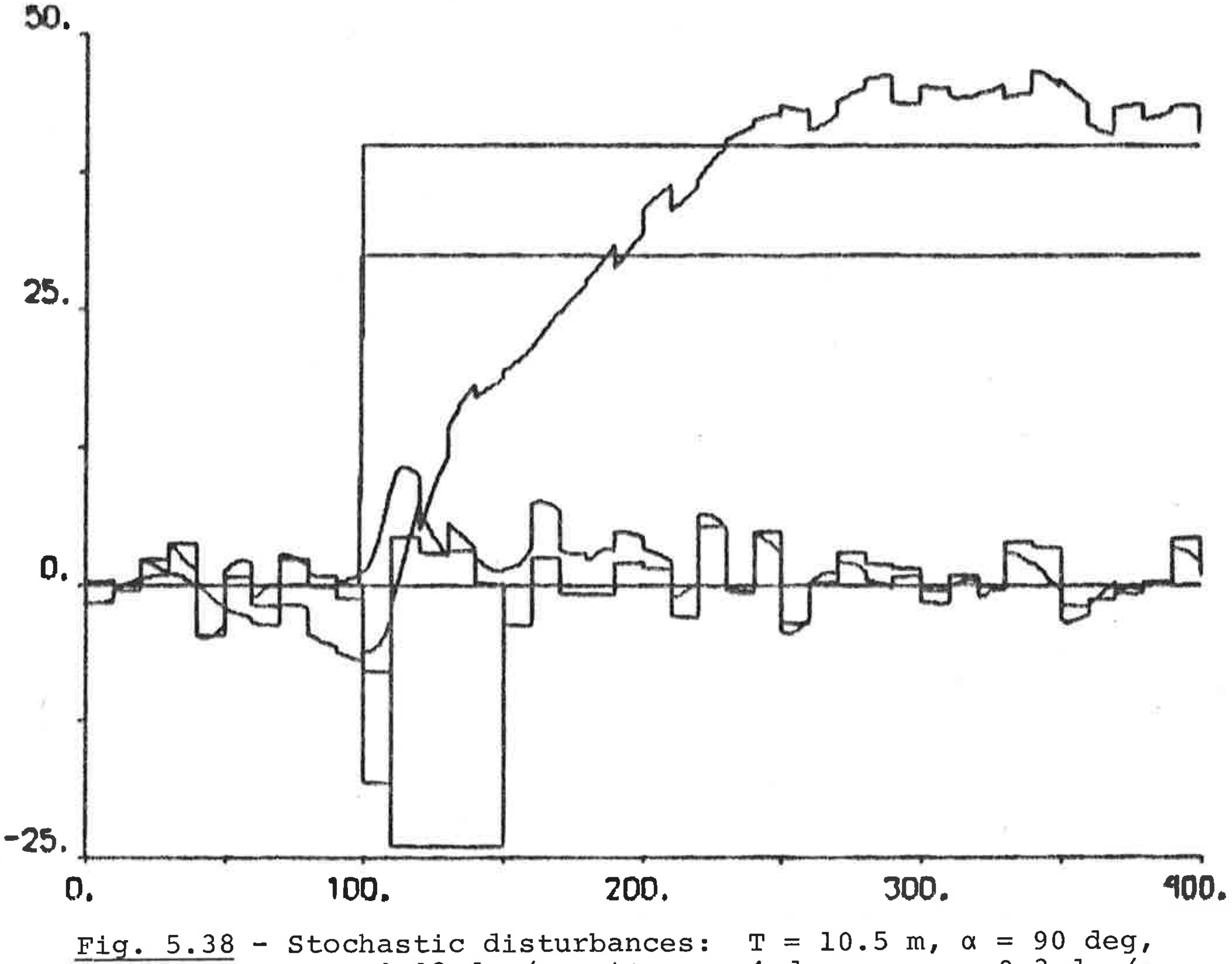
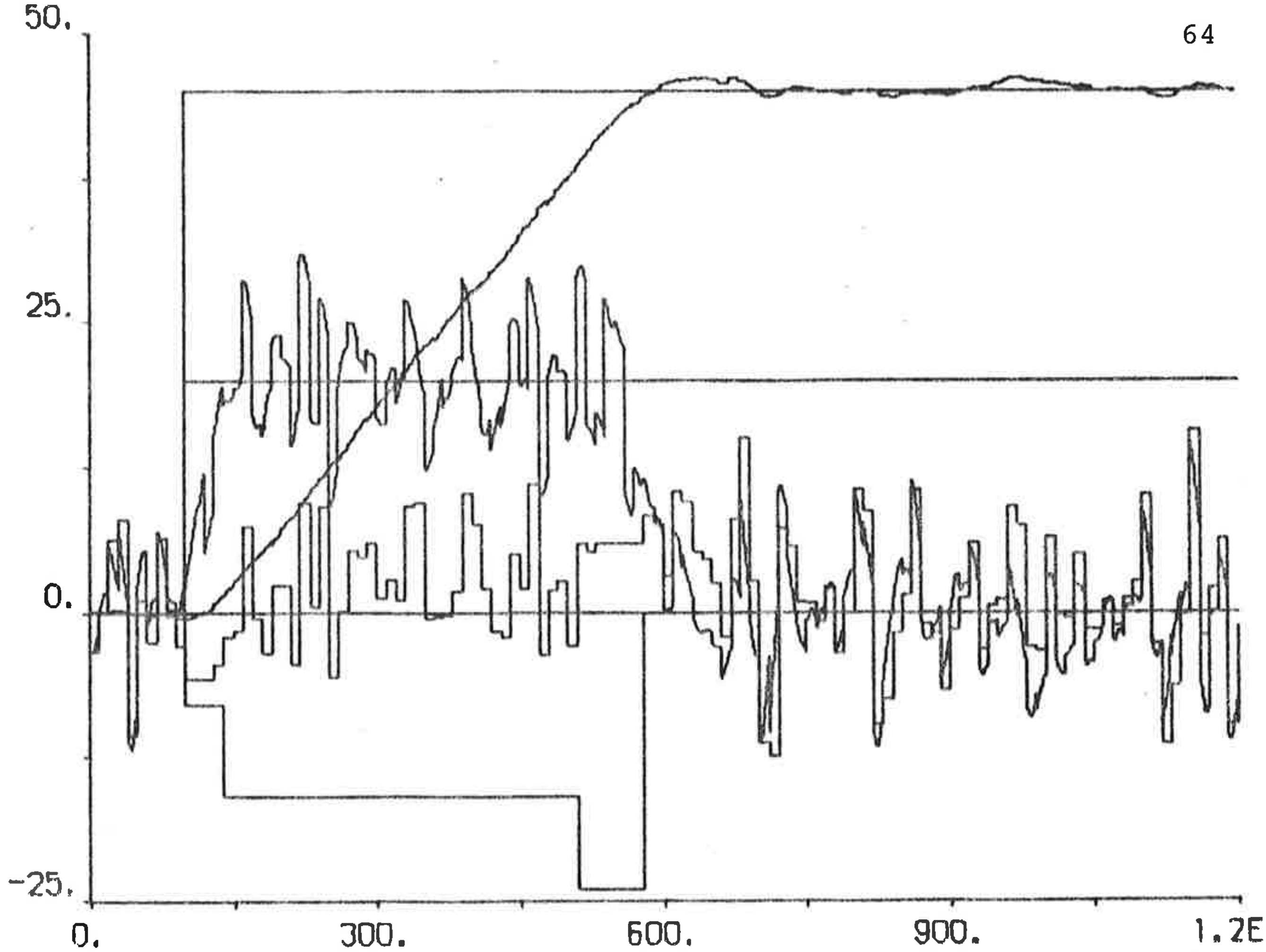


Fig. 5.38 - Stochastic disturbances: $T = 10.5$ m, $\alpha = 90$ deg, $\sigma_r = 0.02$ deg/s, $\Delta\psi_{ref} = 4$ deg, $r_{ref} = 0.3$ deg/s.



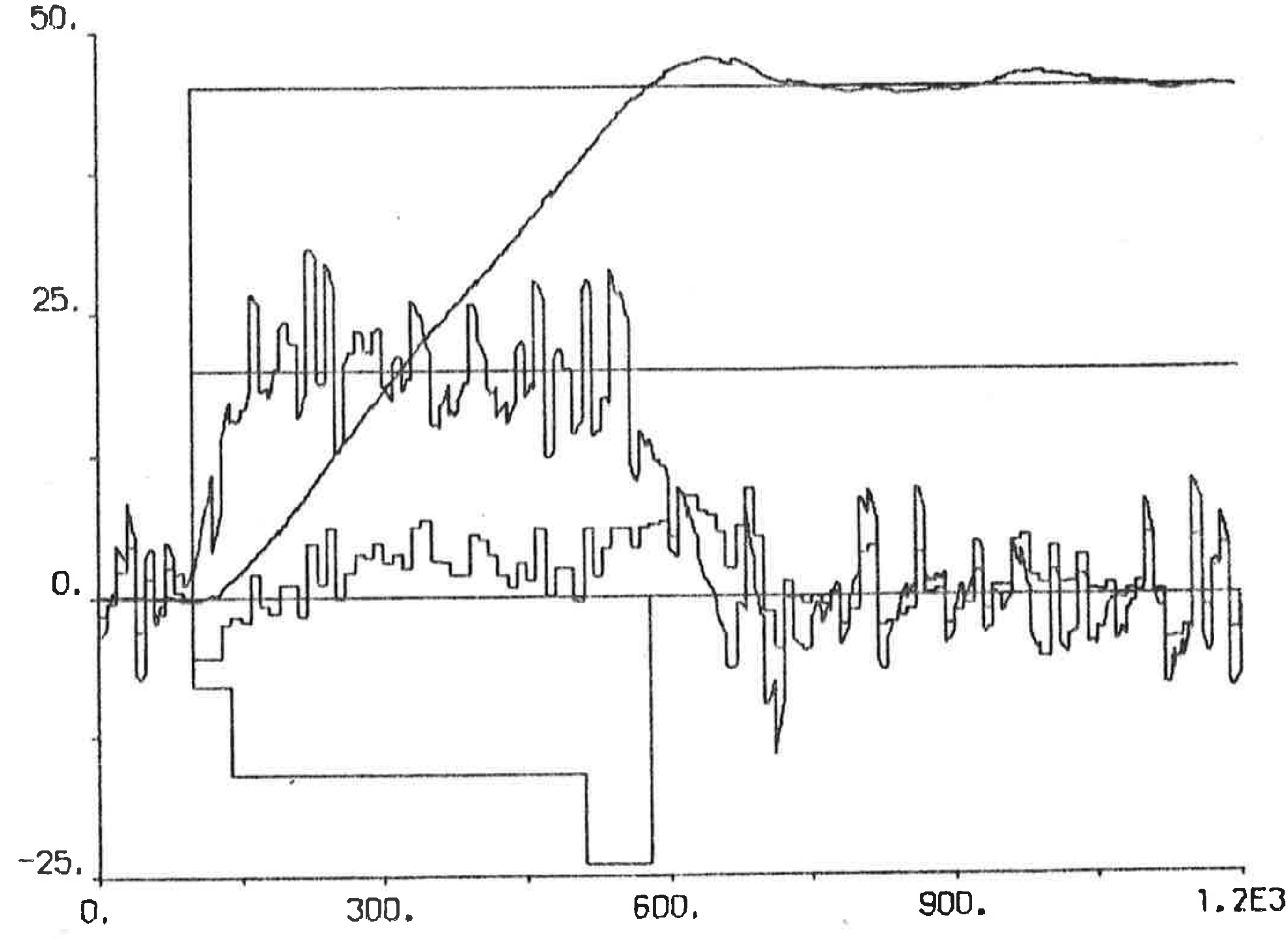


Fig. 5.39 - Stochastic disturbances: $T = 22.3$ m, $\alpha = 90$ deg, $\sigma_r = 0.02$ deg/s, $\Delta\psi_{ref} = 45$ deg, $r_{ref} = 0.1$ deg/s.

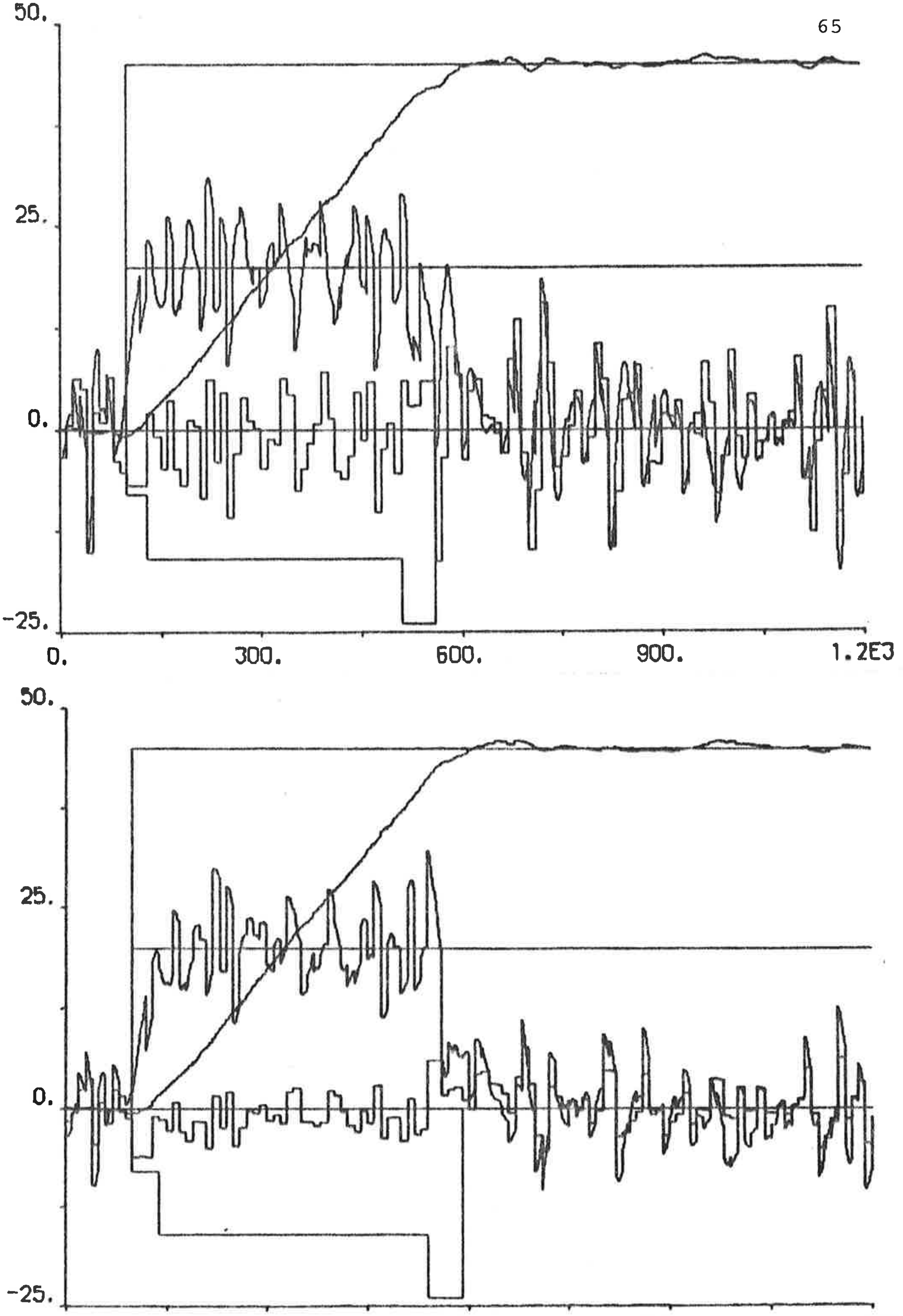


Fig. 5.40 - Stochastic disturbances: $T = 10.5$ m, $\alpha = 90$ deg, $\sigma_r = 0.02$ deg/s, $\Delta\psi_{ref} = 45$ deg, $r_{ref} = 0.1$ deg/s.

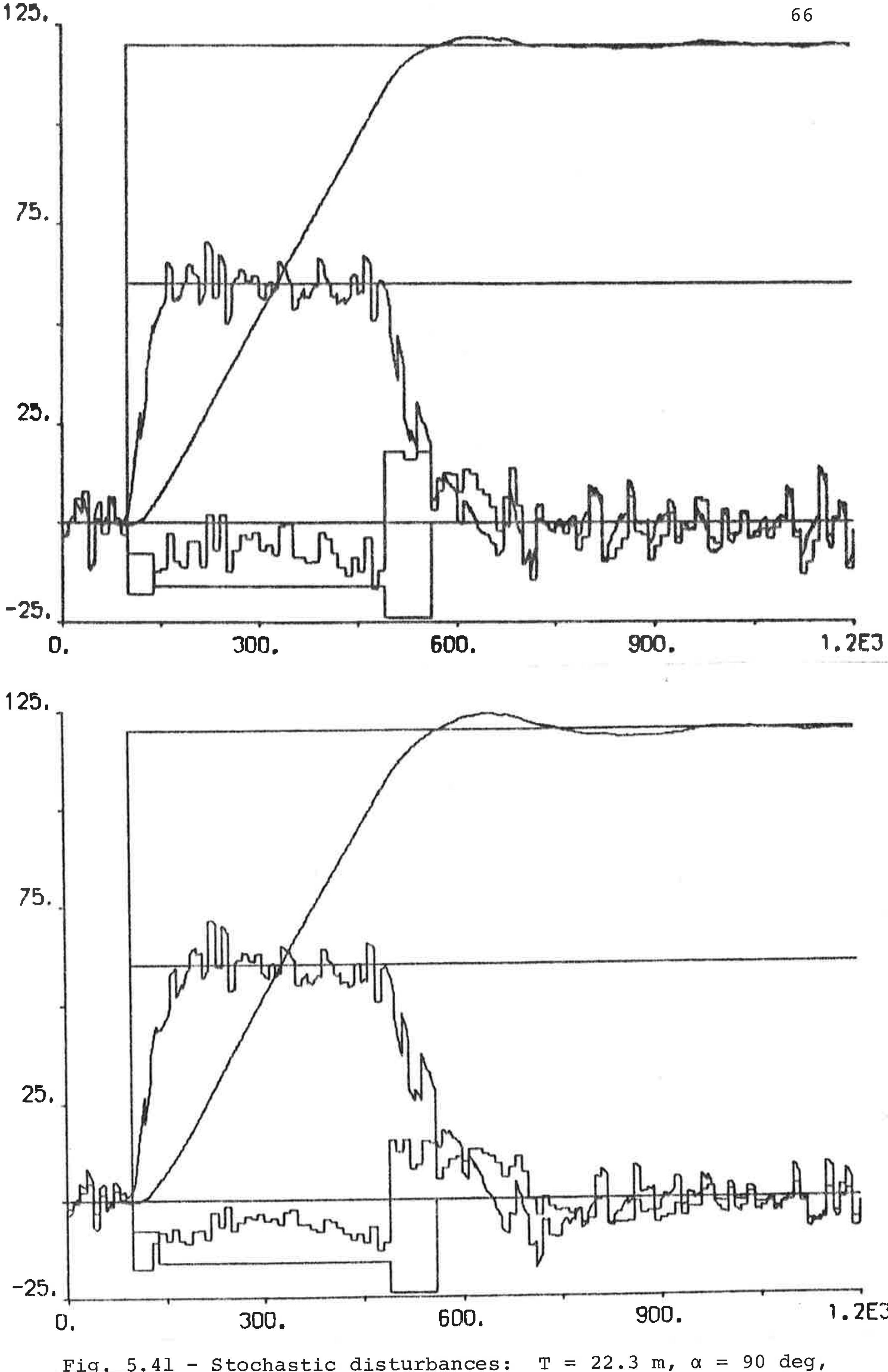


Fig. 5.41 - Stochastic disturbances: $T = 22.3$ m, $\alpha = 90$ deg, $\sigma_r = 0.02$ deg/s, $\Delta\psi_{ref} = 120$ deg, $r_{ref} = 0.3$ deg/s.

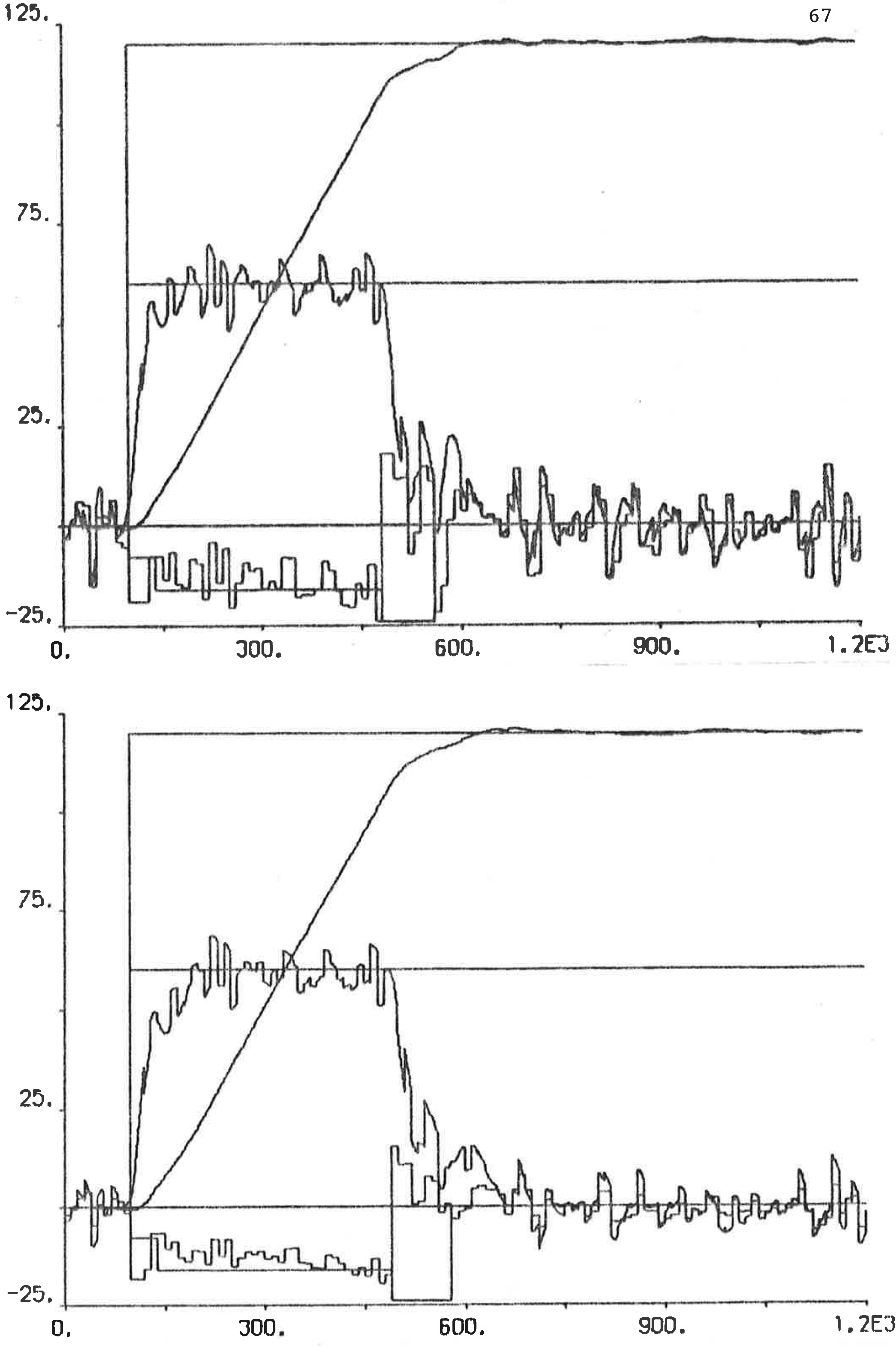


Fig. 5.42 – Stochastic disturbances: $T = 10.5$ m, $\alpha = 90$ deg, $\sigma_r = 0.02$ deg/s, $\Delta\psi_{ref} = 120$ deg, $r_{ref} = 0.3$ deg/s.

6. CONCLUSIONS

The simulations have shown that a yaw regulator consisting of different discrete, fixed gain PID-regulators is able to perform quite satisfactoring yaws of a 350 000 tdw tanker in both full load condition and ballast condition. It is not necessary to change the parameters of the yaw regulator when the load is changed, but it is, however, possible to improve the performance of the yaw regulator if information of the draught is available. Only full speed simulations have been performed. It is, of course, necessary to introduce speed-dependent parameters of the yaw regulator to obtain a good performance for all speeds.

Two sets of yaw regulator parameters have been tested. The simulations have shown that the first parameter set, containing rather large gain factors, is preferable. If, however, the yaw rate signal is very noisy, the second parameter set with smaller gain factors may be considered to decrease the rudder deviations.

7. REFERENCES

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APPENDIX - PROGRAM LISTINGS

```
CONNECTING SYSTEM T1

TIME T

W1ATANK1A=0.
W2ATANK1A=0.
EE1ATANK1A=0.
EE2ATANK1A=0.
DELCATANK1A=DELO

DELO:10.

END
```

```
CONNECTING SYSTEM T2
W1ÄTANK1Å=0.
W2ÄTANK1Å=0.
EE1ÄTANK1Å=0.
EE2ÄTANK1Å=0.
DELCÄTANK1Å=DOUTÄZIGÅ
PSÄZIGÅ=PSIMNÄTANK1Å
DELZÄZIGÅ=DOUTÄZIGÅ
PSINN=-PSIMNÄTANK1Å
END
```

```
CONNECTING SYSTEM T3
₣
TIME T
₣
W1ÄTANK1Å=0.
W2ÄTANK1Å=0.
EE1ÄTANK1Å=0.
EE2ÄTANK1Å=0.
RREFÄYAW1Å=IF T<T0 THEN 0. ELSE R0
PREFÄYAW1Å=IF T<T0 THEN 0. ELSE PSI0
RÄYAW1Å=RMNÄTANK1Å
PSIÄYAW1Å=PSIMNÄTANK1Å
DELCÄTANK1Å=DELCÄYAW1Å
RSC=SC*RMNÄTANK1Å
RFSC=IF T<T0 THEN 0. ELSE R0*SC
PSC=SCP*PSIMNÄTANK1Å
PFSC=IF T<T0 THEN 0. ELSE PSI0*SCP
ZERO=0.
₣
PSI0:45.
R0:0.1
T0:99.99
SC:200.
SCP:1.
₣
END
```

```
CONNECTING SYSTEM T5
₣
TIME T
₣
X1ÄLPFI1Å=E1ÄNOIS1Å
X1ÄLPFI2Å=E2ÄNOIS1Å
W1ÄTANK1Å=X0ÄLPFI1Å
W2ÄTANK1Å=X0ÄLPFI2Å
EE1ÄTANK1Å=E1ÄNOIS2Å
EE2ÄTANK1Å=E2ÄNOIS2Å
RREFÄYAW1Å=IF T<T0 THEN 0. ELSE R0
PREFÄYAW1Å=IF T<T0 THEN 0. ELSE PSI0
RAYAW1Å=RMNÄTANK1Å
PSIÄYAW1Å=PSIMNÄTANK1Å
DELCÄTANK1Å=DELCÄYAW1Å
RSC=SC*RMNÄTANK1Å
RFSC=IF T<T0 THEN 0. ELSE R0*SC
PSC=SCP*PSIMNÄTANK1Å
PFSC=IF T<T0 THEN 0. ELSE PSI0*SCP
ZERO=0.
₣
PSI0:45.
R0:0.1
T0:99.99
SC:200.
SCP:1.
₣
END
```

```
CONTINUOUS SYSTEM ZIG
TIME T
INPUT PS DELZ
OUTPUT DOUT
DOUT=IF T<10 THEN DELO ELSE IF -PS<DELZ THEN DELO ELSE -DELO
DELO:10
END
```

```
CONTINUOUS SYSTEM TANK1

INPUT DELC W1 W2 EE1 EE2

₣DELC = RUDDER COMMAND ÄDEGÅ
₣W1   =FILTERED NOISE ÄM/(S*S)Å
₣W2   =FILTERED NOISE Ä1/(S*S)Å
₣EE1  =MEASUREMENT NOISE ÄDEG/SÅ
₣EE2  =MEASUREMENT NOISE ÄDEGÅ

OUTPUT RMN PSIMN

₣RMN = YAW RATE INCL. NOISE ÄDEG/SÅ
₣PSIMN= HEADING INCL. NOISE ÄDEGÅ

STATE DEL U V R PSI X Y

₣DEL   = RUDDER ANGLE ÄRADÅ
₣U     = FORWARD VELOCITY ÄM/SÅ
₣V     = SWAY VELOCITY ÄM/SÅ
₣R     = YAW RATE Ä1/SÅ*100
₣PSI   = HEADING ÄRADÅ
₣X     = X-COORDINATE ÄKMÅ
₣Y     = Y-COORDINATE ÄKMÅ

DER DDEL DU DV DR DPSI DX DY

INITIAL

U01=U0/CMK
U=U01
SGL=SQRT(G*L)

F1=(22.3-TT)/11.8
F2=(TT-10.5)/11.8
N=1.46*U0/(17.25*F1+15.8*F2)

TS1 = 1/TS
TS2 = TS1/CRG
DL1 = DL/CRG

XUD=XUD1*F1+XUD2*F2
XUDL=XUD*L
XUU=(XUU1*F1+XUU2*F2)/XUDL
XVR=(XVR1*F1+XVR2*F2)/XUD
XRR=(XRR1*F1+XRR2*F2)*L/XUD
XUV=XUVVV/(G*L*XUDL)
XUUDD=(XUDD1*F1+XUDD2*F2)/XUDL
XT=X1T/XUD

YVD=YVD1*F1+YVD2*F2
YVDL=YVD*L
YRU1=YRU/YVD
YRUU1=YRUU/(SGL*YVD)
YUV=(YUV1*F1+YUV2*F2)/YVDL
YUUV=(YUUV1*F1+YUUV2*F2)/(SGL*YVDL)
YVV=(YVV1*F1+YVV2*F2)/YVDL
YRAV=(YRAV1*F1+YRAV2*F2)/YVD
YARV=(YARV1*F1+YARV2*F2)/YVD
YUUD=(YUUD1*F1+YUUD2*F2)/YVDL
YTD1=YTD/YVD
KTY1=KTY/YVD
```

```
NRDL=NRD*L
NRDLL=NRDL*L
NRU=(NRU1*F1+NRU2*F2)/NRDL
NRUU=(NRUU1*F1+NRUU2*F2)/(SGL*NRDL)
NUV=(NUV1*F1+NUV2*F2)/NRDLL
NUUV=(NUUV1*F1+NUUV2*F2)/(SGL*NRDLL)
NVV=(NVV1*F1+NVV2*F2)/NRDLL
NRR=(NRR1*F1+NRR2*F2)/NRD
NRAV=(NRAV1*F1+NRAV2*F2)/NRDL
NARV=(NARV1*F1+NARV2*F2)/NRDL
NUUD=(NUUD1*F1+NUUD2*F2)/NRDLL
NTD1=NTD/NRDL
KTN1=KTN/NRDL

XF=FW/XUD
YF=FW/YVD
NF=FW*LV/NRDLL

JJ1=(1-W)/(N*D)
DISPL=DISP1*F1+DISP2*F2
TT1=N*N*D*D*D*D/DISPL
JJ=U01*JJ1
JJP=JJ/SQRT(1+JJ*JJ)
KKT=-0.33*JJP*JJP-0.38*JJP+0.35
TM0=KKT*(1+JJ*JJ)*TT1
LL1=CMK*L1
ALF1=ALFA/CRG

OUTPUT

RM=CRG*R/100.
RMN=RM+EE1
PSIM=CRG*PSI
PSIMN=PSIM+EE2
DELM=CRG*DEL
UM=CMK*U
VM=CMK*V
V1=LL1*R/100.+CMK*V
VV=SQRT(UM*UM+VM*VM)
BETA=-CRG*ATAN(V/U)

DYNAMICS

RR=R/100.
APSI=ALF1-PSI
SINW=SIN(APSI)
SINP=SIN(PSI)
COSP=COS(PSI)
J=U*JJ1
JP=J/SQRT(1+J*J)
KT=-0.33*JP*JP-0.38*JP+0.35
TM=KT*(1+J*J)*TT1
TM1=IF TM<TM0 THEN TM ELSE TM0
TMD =TM1*DEL
U2=U*U
AV=ABS(V)
AR=ABS(RR)
RU=RR*U
RU2=RU*U
UV=U*V
U2V=U*UV
VAV=V*AV
RAV=RR*AV
ARV=AR*V
```

```
U2D=U2*DEL
DDEL1=-TS1*DEL+TS2*DELC
DDEL=IF DDEL1<-DL1 THEN -DL1 ELSE IF DDEL1>DL1 THEN DL1 ELSE DDEL1

DU=XUU*U2+XVR*V*RR+XRR*RR*RR+XUV*UV*VAV+XUUDD*U2D*DEL+XT*TM-XF*COS(APSI)

SL=YRU1*RU+YRUU1*RU2+YUV*UV+YUUV*U2V+YVV*VAV+YRAV*RAV
DV=YARV*ARV+YUUD*U2D+YTD1*TMD+KTY1*TM-YF*SINW+W1/YVD+SL
SL1=NRU*RU+NRUU*RU2+NUV*UV+NUUV*U2V+NVV*VAV+NRR*RR*AR
DR=(SL1+NRAV*RAV+NARV*ARV+NUUD*U2D+NTD1*TMD+KTN1*TM+NF*SINW+W2/NRD)*100.

DPSI=RR
DX=(U*COSP-V*SINP)/1000.
DY=(U*SINP+V*COSP)/1000.

G:9.80665
CMK:1.943844
CRG:57.2958
L:350.
UD:15.8
TT:22.3
TS:5.0
DL:2.32   #2 PUMPS
XUD1: [redacted]
XUD2:
XUU1:
XUU2:
XVR1:
XVR2:
XRR1:
XRR2:
XUVVV:
XUDD1:
XUDD2:
X1T:
YVD1:
YVD2:
YRU:
YRUU:
YUV1:
YUV2:
YUUV1:
YUUV2:
YVV1:
YVV2:
YRAV1:
YRAV2:
YARV1:
YARV2:
YUUD1:
YUUD2:
YTD:
KTY:
NRD:
NRU1:
NRU2:
NRUU1:
NRUU2:
NUV1:
NUV2:
NUUV1:
NUUV2:
NVV1:
NVV2:
```

```
NRR1:[illegible]
NRR2:[illegible]
NRAV1:[illegible]
NRAV2:[illegible]
NARV1:[illegible]
NARV2:[illegible]
NUUD1:[illegible]
NUUD2:[illegible]
NTD:-[illegible]
KTN:-[illegible]

FW:0.
LV:25.
W:0.02
D:0.1
DISP1:1724[illegible]
DISP2:389[illegible]
L1:164.35
ALFA:0.

END
```

```
DISCRETE SYSTEM YAW1
₣
INPUT R PSI RREF PREF
₣
₣R     =YAW RATE ÄDEG/SÅ
₣PSI   =HEADING ÄDEGÅ
₣RREF  =REF. VALUE OF YAW RATE ÄDEG/SÅ
₣PREF  =REF. VALUE OF HEADING ÄDEGÅ
₣
OUTPUT DELC
₣
₣DELC =RUDDER COMMAND ÄDEGÅ
₣
TIME T
₣
STATE PRO MODY MDEL STD INT1 INT2  TF1 TF3
₣
₣PRO   =OLD REF. VALUE OF HEADING ÄDEGÅ
₣MODY  =YAW INDICATOR
₣MDEL  =MEAN VALUE OF RUDDER ÄDEGÅ
₣STD   =WEIGHTING FACTOR
₣INT1  =INTEGRAL TERM OF PHASE 0
₣INT2  =INTEGRAL TERM OF PHASE 2
₣TF1   =TIME PHASE 1
₣TF3   =TIME PHASE 3
₣
NEW NPRO NMODY NMDEL NSTD NINT1 NINT2  NTF1 NTF3
₣
TSAMP TS
₣
INITIAL
₣
STD=1.-BD
₣
OUTPUT
₣
S1=ABS(PREF-PRO)
S2=PSI-PREF
S3=R-RREF
DD1=K4*S3
DR1=ABS(C1*RREF)
D1=IF DD1<-DR1 THEN -DR1 ELSE IF DD1>DR1 THEN DR1 ELSE DD1
DD2=K7*S2+K8*R
DR2=ABS(C3*RREF)
D2=IF DD2<-DR2 THEN -DR2 ELSE IF DD2>DR2 THEN DR2 ELSE DD2
₣
M1=IF MODY<0.5 AND S1>PSIMX THEN 1. ELSE 0.
MA=IF M1>0.5 OR (MODY>0.5 AND MODY<1.5) THEN 1. ELSE 0.
MM1=IF MA>0.5 AND RREF>0. AND S3>-EPS1 THEN 1. ELSE 0.
MM2=IF MA>0.5 AND RREF<0. AND S3<EPS1 THEN 1. ELSE 0.
M2=IF MM1>0.5 OR MM2>0.5 OR TF1>T1 THEN 1. ELSE 0.
MB=IF M2>0.5 OR (MODY>1.5 AND MODY<2.5) THEN 1. ELSE 0.
MM3=IF (MA>0.5 OR MB>0.5) AND S2<0. AND -C2*R<S2 THEN 1. ELSE 0.
MM4=IF (MA>0.5 OR MB>0.5) AND S2>0. AND -C2*R>S2 THEN 1. ELSE 0.
M3=IF MM3>0.5 OR MM4>0.5 THEN 1. ELSE 0.
MC=IF M3>0.5 OR MODY>2.5 THEN 1. ELSE 0.
MC1=IF MC>0.5 AND ABS(R)<EPS2 THEN 1. ELSE 0.
MC2=IF MC>0.5 AND RREF>0. AND S2>-EPS3 THEN 1. ELSE 0.
MC3=IF MC>0.5 AND RREF<0. AND S2<EPS3 THEN 1. ELSE 0.
M4=IF MC1>0.5 OR MC2>0.5 OR MC3>0.5 OR TF3>T3 THEN 1. ELSE 0.
MD=IF M3<0.5 AND M4<0.5 THEN 0. ELSE 1.
ME=IF M3>0.5 AND M4<0.5 THEN 1. ELSE 0.
MF=IF M2>0.5 AND MD<0.5 THEN 1. ELSE 0.
```

```
MG=IF M1>0.5 AND M2<0.5 AND MD<0.5 THEN 1. ELSE 0.
MM5=IF MG>0.5 THEN 1. ELSE IF MF>0.5 THEN 2. ELSE 0.
MM6=IF ME>0.5 THEN 3. ELSE IF M4>0.5 THEN 0. ELSE MODY
MM=IF MM5>0.5 THEN MM5 ELSE MM6
MMS=MM*SCM
₣
DC0=K1*S2+K2*R+K3*INT1
DC1=D1+MDEL
DC2=K5*S3+K6*INT2+MDEL
DC3=D2
DDC=IF MM<0.5 THEN DC0 ELSE IF MM>0.5 AND MM<1.5 THEN DC1 ELSE 1000.
DC=IF DDC<999. THEN DDC ELSE IF MM>1.5 AND MM<2.5 THEN DC2 ELSE DC3
₣
SS1=MDEL+(STD+BD)*(DC-MDEL)
MH=IF MM>1.5 AND MM<2.5 THEN 1. ELSE 0.
SS2=IF MM<0.5 THEN SS1 ELSE  MDEL
SS3=IF M4>0.5 THEN DC ELSE SS2
SS4=IF M4>0.5 THEN 1.-BD ELSE STD
₣
NPRO=PREF
NMODY=MM
NMDEL=SS3
NSTD=IF MM<0.5  THEN (1.-BD)*SS4/(1.-BD+SS4) ELSE STD
NINT1=IF MM<0.5 THEN INT1+S2*DT ELSE 0.
NINT2=IF MH>0.5 THEN INT2+S3*DT ELSE 0.
NTF1=IF MM>0.5 AND MM<1.5 THEN TF1+DT ELSE 0.
NTF3=IF MM>2.5 THEN TF3+DT ELSE 0.
₣
DELC=DC
₣
TS=T+DT
₣
DT:10.
BD:0.05
PSIMX:2.5
K1:5.
K2:200.
K3:0.005
K4:200.
K5:200.
K6:8.
K7:2.
K8:200.
EPS1:0.
EPS2:0.02
EPS3:1.
C1:60.
C2:50.
C3:60.
T1:30.
T3:80.
SCM:-8.
₣
END
```

```
CONTINUOUS SYSTEM LPFI1
INPUT XI
OUTPUT XO
STATE X1 X2
DER DX1 DX2
INITIAL
X1:0
X2:0
T=TP/6.283185
A1=-2*CS/T
A2=-1/(T*T)
CC2=AK/(T*T)
OUTPUT
XO=CC2*X2
DYNAMICS
DX1=A1*X1+A2*X2+XI
DX2=X1
#
AK:1     #FILTER GAIN
TP:8     #PERIOD TIME OF PEAK FREQ.
CS:0.25 #DAMPING FACTOR
#
#    PEAK GAIN FOR FREQ.=1/TP : AK/(2*CS)
#
END
```

```
CONTINUOUS SYSTEM LPFI2
INPUT XI
OUTPUT XO
STATE X1 X2
DER DX1 DX2
INITIAL
X1:0
X2:0
T=TP/6.283185
A1=-2*CS/T
A2=-1/(T*T)
CC2=AK/(T*T)
OUTPUT
XO=CC2*X2
DYNAMICS
DX1=A1*X1+A2*X2+XI
DX2=X1
₣
AK:1     ₣FILTER GAIN
TP:8     ₣PERIOD TIME OF PEAK FREQ.
CS:0.25 ₣DAMPING FACTOR
₣
₣    PEAK GAIN FOR FREQ.=1/TP : AK/(2*CS)
₣
END
```

```
      SUBROUTINE SYSTS
C
      DIMENSION S(60)
      COMMON/DESTIN/ISYST,IDUM
      COMMON/NSYSTS/NSYST
      COMMON/NALLOC/NS
      COMMON/SAVEAR/IS(18)
C
      NSYST=2
      NS=60
C
      GO TO (1,2),ISYST
C
 1    CALL SNOISE('NOIS1',IS(1),S)
      RETURN
 2    CALL SNOISE('NOIS2',IS(10),S)
      RETURN
      END
```

```
C         SIMNON -
C
C         AN INTERACTIVE SIMULATION PROGRAM
C         FOR NONLINEAR SYSTEMS
C
C         MAIN PROGRAM
C
C         AUTHOR  HILDING ELMQVIST
C
C         REFERENCE
C         ---------
C
C         H. ELMQVIST: SIMNON - AN INTERACTIVE SIMULATION
C                     PROGRAM FOR NONLINEAR SYSTEMS -
C                     USER'S MANUAL
C
C
C         DATA BASE
C         ---------
C
C         /PSCODE/ IPSEUD( )
C                 IPSEUD- PSEUDO CODE AREA
C
C         /VARTAB/ VARS( ),IPNTS( ),ITYPES( )
C                 VARS  - IDENTIFIER TABLE
C                 IPNTS - ADDRESS TABLE
C                 ITYPES- TYPE TABLE
C                         1: TIME
C                         2: STATE
C                         3: INPUT
C                         4: OUTPUT
C                         5: INIT
C                         6: DER
C                         7: NEW
C                         8: TSAMP
C                         9: PAR
C                        10: VAR
C
C         /VALUES/ VALUE( )
C                 VALUE - VALUE TABLE AND LITTERAL TABLE
C
C         /SYSINF/ NASYST,ASYSTS( ),IVARS( ,2),INFSYS( ),LENTRY( ,3)
C                 NASYST- NUMBER OF ACTIVE SYSTEMS
C                 ASYSTS- SYSTEM IDENTIFIERS FOR ACTIVE SYSTEMS
C                 IVARS - DEFINING THE POSITION OF THE VARIABLE
C                         TABLE FOR EACH SYSTEM
C                 INFSYS- SYSTEM TYPE
C                         1: CONNECTING
C                         2: CONTINUOUS
C                         3: DISCRETE
C                         4: CONTINUOUS (FORTRAN)
C                         5: DISCRETE (FORTRAN)
C                 LENTRY- ENTRY POINTS FOR EACH ACTIVE SYSTEM
C                         ( ,1): INITIAL-SECTION
C                                OR THE NUMBER OF A FORTRAN-SYSTEM
C                         ( ,2): OUTPUT- OR CONNECT-SECTION
C                         ( ,3): DYNAMICS-SECTION
C
C         /EXTCOM/ IEVAL,IERR,TYPE,SYSID,NEXTSY,NS
C                 IEVAL - POINTER IN VARIABLE TABLE
C                 IERR  - ERROR INDICATOR
C                 TYPE  - SYSTEM TYPE FROM SUBROUTINE IDENT
C                         'CONT' OR 'DISCR'
```

```
C               SYSID  - SYSTEM IDENTIFIER FROM SUBROUTINE IDENT
C               NEXTSY- NUMBER OF EXTERNAL SYSTEMS
C               NS     - NUMBER OF ELEMENTS IN THE ALLOCATION AREA
C       /ENTRYS/ NTRINT,NTRDER,NTRSMP
C               NTRINT- ENTRY POINT FOR INITIAL COMPUTATIONS
C               NTRDER- ENTRY POINT FOR COMPUTATIONS OF DERIVATIVES
C               NTRSMP- ENTRY POINT FOR SAMPLING
C
C       /ENTRY/ LENTRY
C               LENTRY- ACTUAL ENTRY POINT FOR CALCUL
C
C       /PNTS/ NXC,NXD,KX( ),KDX( ),KXI( ),KTSAMP( )
C               NXC    - NUMBER OF STATES IN CONTINUOUS SYSTEMS
C               NXD    - NUMBER OF STATES IN DISCRETE SYSTEMS
C               KX     - POINTERS TO STATE VARIABLES
C               KDX    - POINTERS TO DER- AND NEW-VARIABLES
C               KXI    - POINTERS TO INIT-VARIABLES
C               KTSAMP- POINTERS TO TSAMP-VARIABLES
C
C       /COMINF/ (SEE INTRAC)
C
C       /MACINF/ (SEE INTRAC)
C
C       /MESSS/ MESS
C               MESS   - MESSAGE INDICATOR
C
C       /SIMN/ NOSYST,OVFLO,IPLCOM,IEXIT,IWARN,ICOMPU,LDARK
C               ,NOCONT,LLPCOM,INIDRA
C               NOSYST- TRUE IF NO SYSTEM DEFINED
C               OVFLO - TRUE IF OVERFLOW CHECK PERFORMED
C               IPLCOM- TRUE IF PLOT-COMMAND SHOULD BE WRITTEN
C               IEXIT - TRUE IF THE EDITOR IS TO MAKE
C                       AUTOMATIC EXIT (SYST)
C               IWARN - TRUE IF WARNINGS SHOULD BE WRITTEN
C               ICOMPU- TRUE IF MESSAGE ABOUT COMPUTATIONS
C                       IN OUTPUT-SECTION SHOULD BE GIVEN
C               LDARK - TRUE IF NOT VISABLE LINES AT SAMPLINGS
C               NOCONT- TRUE IF CONTINUATION OF THE SIMULATION
C                       IS NOT POSSIBLE
C               LLPCOM- TRUE IF COMMANDS SHOULD BE ECHOED ON THE LP
C               INIDRA- TRUE IF INITIALIZATION OF DRAW
C
C       /PLT/ NPLT,IVADR( ),IHADR,PLTCOM( )
C               NPLT   - NUMBER OF PLOT-VARIABLES
C               IVADR  - POINTERS TO VERTICAL VARIABLES
C               IHADR  - POINTER TO HORIZONTAL VARIABLE
C               PLTCOM- BUFFER FOR PLOT-COMMAND
C
C       /STOVAR/ NSTV,IVARS( ),ISYSS( )
C               NSTV   - NUMBER OF VARIABLES TO BE STORED
C               IVARS  - POINTERS TO VARIABLE NAMES
C               ISYSS  - POINTERS TO SYSTEM IDENTIFIERS
C
C       /DATCOM/ FILE,DTF
C               FILE   - STORE FILE NAME
C               DTF    - MINIMAL TIME INCREMENT
C
C       /SHOVAR/ NSHVAR
C               NSHVAR- NUMBER OF SHOWED VARIABLES SINCE AXES
C
C       /AX/ HMIN,DH,VMIN,DV
C               HMIN   - HORIZONTAL MINIMUM
C               DH     - HORIZONTAL VALUE PER CENTIMETER
C               VMIN   - VERTICAL MINIMUM
```

```
C                 DV     - VERTICAL VALUE PER CENTIMETER
C
C         /ERRWEI/ EPS,WEIGHT( )
C                 EPS    - ERROR BOUND
C                 WEIGHT- ERROR WEIGHTS
C
C         /ALG/ IALG
C                 IALG   - SPECIFIES INTEGRATION ALGORITHM
C                          1: HAMPC
C                          2: RK
C                          3: RKFIX
C
C         /MARKS/ IMARK,MRK,TMRK,DTMRK
C                 IMARK - TRUE IF MARKS WANTED
C                 MRK    - SPECIFIES WHICH MARKS
C                 TMRK   - TIME FOR NEXT MARKS
C                 DTMRK - TIME DISTANCE BETWEEN MARKS
C
C         /USER/ LSTOP,LDARK,LCALUS,NRESUM,LFIRST,NOPLOT
C                 LSTOP - TRUE IF SIMULATION SHOULD BE STOPPED
C                 LDARK - TRUE IF DARK LINE
C                 LCALUS- TRUE IF THE SUBROUTIEN USRSUB SHOULD BE CALLED
C                 NRESUM- NUMBER OF DISCRETE SYSTEMS THAT HASN'T
C                          PRODUCED A DISCONTINUITY
C                 LFIRST- TRUE IF SYSTS CALLED FIRST TIMES
C                 NOPLOT- IF TRUE NO PLOT
C
C         /DESTIN/ ISYST,IPART
C                 ISYST - SYSTEM NUMBER
C                 IPART - PART NUMBER
C
C         /NSYSTS/ NSYST
C                 NSYST - NUMBER OF EXTERNAL SYSTEMS
C
C         /NALLOC/ NALL
C                 NALL   - NUMBER OF ELEMENTS IN THE ALLOCATION AREA
C
C         /TIME/ T
C                 T      - THE SIMULATION TIME
C
C         /STATES/ X( )
C                 X      - STATES OF CONTINUOUS SYSTEMS
C
C         /DERS/ DX( )
C                 DX     - DERIVATIVES OF THE STATES
C
C         /CMPVAR/ MODE,IASYST,ISYTYP,IERR,IVAR1,IVAR2,IVAL1,IVAL2
C                 L,LENTR1,LENTR2,LENTR3
C                 MODE   - COMPILER MODE
C                          1: SYSTEM HEADING
C                          2:
C                          3: DECLARATIONS
C                          4:
C                          5: INITIAL-SECTION
C                          6: OUTPUT-SECTION
C                          7: DYNAMICS-SECTION
C                          8: CONNECT-SECTION
C                          9: END
C                 IASYST- INDEX FOR ACTUAL SYSTEM
C                 ISYTYP- SYSTEM TYPE
C                          1: CONNECTING
C                          2: CONTINUOUS
C                          3: DISCRETE
C                 IERR   - ERROR FLAG
```

```
C                  IVAR1 - INDEX FOR LOWER BOUND IN VARIABLE TABLE
C                  IVAR2 - INDEX FOR UPPER BOUND IN VARIABLE TABLE
C                  IVAL1 - POINTER IN THE VALUE TABLE
C                  IVAL2 - POINTER IN THE LITTERAL TABLE
C                  L     - POINTER IN THE PSEUDO CODE AREA
C                  LENTR1- POINTER TO INITAL-SECTION
C                  LENTR2- POINTER TO OUTPUT- OR CONNECT-SECTION
C                  LENTR3- POINTER TO DYNAMICS-SECTION
C
C         /NXPNT/  NXP( ,2)
C                  NXP   - SPECIFIES WHICH STATES THAT BELONGS
C                          TO EACH DISCRETE SYSTEM
C
C         /COND/  LSAMP,LSAMPS( )
C                  LSAMP - TRUE IF SAMPLING IS TO BE DONE
C                  LSAMPS- SPECIFIES WHICH SYSTEMS THAT IS TO BE SAMPLED
C
C         /LIMITS/ MPSC,MVAR,MVAL,MX
C                  MPSC  - NUMBER OF ELEMENTS IN PSEUDO CODE AREA
C                  MVAR  - NUMBER OF ELEMENTS IN VARIABLE TABLE
C                  MVAL  - NUMBER OF ELEMENTS IN VALUE TABLE
C                  MX    - MAXIMUM NUMBER OF STATES
C
C         /SIMARG/ T1,T2,DT,LCONT,LMARK
C                  T1-     START TIME
C                  T2-     STOP TIME
C                  DT-     TIME INCREMENT
C                  LCONT-  LOGICAL VARIABLE TO INDICATE IF CONTINUATION
C                          OF SIMULATION IS WANTED
C                  LMARK-  LOGICAL VARIABLE INDICATING IF MARKS IS WANTED
C                          DURING THE PLOTTING
C
C         /ARGSAV/ H1,H2,V1,V2
C                  H1    - LAST HORIZONTAL MINIMUM (AXES)
C                  H2    - LAST HORIZONTAL MAXIMUM
C                  V1    - LAST VERTICAL MINIMUM
C                  V2    - LAST VERTICAL MAXIMUM
C
C         /AXINF/ IX0,IY0,XAX,YAX
C                  IX0,IY0 - ORIGO FOR AXES (TEKPOINTS)
C                  XAX,YAX - LENGTH OF AXES (CM)
C
C
C
C         SUBROUTINE REQUIRED
C                  ISIMN
C                  ESIMN
C                  SIMNSY
C                  SIMU
C
C
      COMMON/ALLCOM/IDD(3)
      COMMON /PSCODE/ IDUM1(4000)
      COMMON /VARTAB/ IDUM2(1000),DUM2(500)
      COMMON /VALUES/ DUM3(500)
      COMMON /SYSINF/ IDUM4(151),DUM4(25)
      COMMON /EXTCOM/ IDUM5(4),DUM5(2)
      COMMON /ENTRYS/ IDUM6(3)
      COMMON /ENTRY/  IDUM7
      COMMON /PNTS/   IDUM8(177)
      COMMON /COMINF/ IDUM9(33),DUM9(41)
      COMMON /MACINF/ IDUM10(191),DUM10(107)
      COMMON /MESSS/  IDUM11
      COMMON /SIMN/   IDUM12(10)
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      COMMON /PLT/    IDUM13(12),DUM13(16)
      COMMON /STOVAR/ IDU135(101)
      COMMON /DATCOM/ DUM136(2)
      COMMON /SHOVAR/ IDU137
C ***** HCOPY *****
      COMMON/HCPCOM/DUM138(10),IDU138(30)
C ***** HCOPY *****
      COMMON /AX/     DUM14(4)
      COMMON /ERRWEI/ DUM15(51)
      COMMON /ALG/    IDUM16
      COMMON /MARKS/  IDUM17(2),DUM17(2)
      COMMON /USER/   IDUM18(6)
      COMMON /DESTIN/ IDUM19(2)
      COMMON /NSYSTS/ IDM191
      COMMON /NALLOC/ IDM192
      COMMON /TIME/   DUM20
      COMMON /STATES/ DUM21(50)
      COMMON /DERS/   DUM211(50)
      COMMON /CMPVAR/ IDUM23(12)
      COMMON /NXPNT/  IDUM24(50)
      COMMON /COND/   IDUM25(26)
      COMMON /LIMITS/ MPSC,IDM261,MVAL,MX
      COMMON /SIMARG/ IDUM26(2),DUM26(3)
      COMMON /ARGSAV/ DUM0(4)
      COMMON /AXINF/ IDUM27(2),DUM27(2)
C
C
      MPSC=4000
      MVAL=500
      MX=20
      CALL LOGG(0)
      CALL LPHDL(0)
C
      CALL ISIMN
C
      MODE=1
 10   CALL ESIMN(MODE)
C
      GOTO(1,2,3,4),MODE
C
 1    CALL LPHDL(1)
      CALL LOGG(1)
      STOP
C
 2    CALL SIMNSY
      GO TO 10
C
 3    CALL SIMU
      GO TO 10
C
 4    CALL LPHDL(2)
          CALL LOGG(2)
      STOP
      END
```