THE TUBSAT-1 ATTITUDE CONTROL AND STABILIZATION SYSTEM

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ABSTRACT

TUBSAT-1 (Technical University Berlin Satellite) is an experimental low-cost satellite being financed by the German BMFT.

The dimensions and weight are determined by the NASA Gas-Program and it will be ejected from the Space Shuttle within the German spacelab mission D2 by December 19, 1991, into a 298 km circular orbit and at a 28.5° inclination.

To enable a large variety of useful experiments to fly with TUBSAT, it was necessary to develop a rather precise attitude control and stabilization (ACS) system.

The ACS should be low cost, flexible (in view of changing ACS modes and parameters during the mission time), minimum component number and a low power consumption.

A sun/star orientation with an additional spin mode was chosen and developed. The system is based on a microcomputer, fixed momentum wheel (FMW), one magnetic torquer, one sun and two star sensors. The closed loop pitch control consists of FMW, sun and star (for the eclipse phase) sensors, achieving a pitch pointing accuracy of 0.26° for any slew maneuver by using momentum transfer from the wheel to the satellite.

Control of the wheel momentum (desaturation) without affecting the pitch axis orientation can be accomplished by executing a pitch slew maneuver. Positioning the magnetic torquer (which is mounted perpendicular to the pitch axis) to interact with the geomagnetic field vector.

The pitch axis reorientation maneuver due to interaction between the magnetic torquer and the magnetic field vector component can be controlled by the one axis star sensor (roll/yaw rotation). A further pitch slew maneuver of 90° is necessary for positioning the sensor (roll = yaw).

This means achieving the target attitude regardless of the momentum change.

THE TUBSAT-1

ATTITUDE CONTROL AND STABILISATION SYSTEM

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TUBSAT-1 (Technical University Berlin Satellite) is an experimental low-cost satellite being financed by the German BMFT. The dimensions and weight are determined by the NASA Gas-Program and it will be ejected from the space shuttle within the German spacelab mission D2 by February 6th. 1992, into a 298 km circular orbit and at a 28.5° inclination. To enable a large variety of useful experiments to fly with TUBSAT, it was necessary to develop a rather precise attitude control and stabilisation (ACS) system. The ACS should be low cost, flexible (inview of changing ACS modes and parameters during the mission time), should have a minimum component number and a low power consumption. A sun/star orientation with an additional spin mode was chosen and developed. The system is based on a microcomputer, fixed momentum wheel (FMW), one magnetic torquer, one sun- and two starsensors. The closed loop pitch control consits of FMW, sun- and star (for the eclipse phase) sensors,achieving a pitch pointing accuracy of 0.26° for any slew maneuver by using momentum transfer from the wheel to the satellite. Control of the wheel momentum (desaturation) without significantly affecting the pitch axis orientation can be accomplished by executing a pitch slew maneuver, positioning the magnetic torquer (which is mounted perpendicular to the pitch axis) to interact with the geomagnetic field vector. The pitch axis reorientation maneuver due to interaction between the magnetic torquer and the magnetic field vector component can be controlled by the one axis star sensor (roll/yaw rotation). A further pitch slew maneuver of 90° is necessary for positioning the sensor (roll $\rightleftarrows$ yaw). This means achieving the target attitude regardless of the momentum change.

1. TUBSAT program

TUBSAT-1 can be defined as a first step into the direction of multimission flight vehicle which is particularily suited for educational purposes and student experiments with the following aims:

- Demonstration of a modular experimental platform which is adaptable to low cost launch opportunities for achieving high launch frequencies.
- Test of a "self made" low-cost digital ACS concept within a small space craft to implement a fairly precise orientation in orbit.
- Execution of a pilot project for observing the migratory routes of white storks from Europe to Africa and/or back.
- Store and forward communication experiments between student groups.

2. ACS system and components

TUBSAT-1 should by definition have a 3-axis stabilisation and control system with the following requirements:

- Use of space environment influence only
- Low-cost
- A minimum number of components with a relatively low mass, power consumption and volume
- Fairly precise pointing accuracies

Different possibilities of ACS concept have been discussed. The final decision was made after quite a long period according to the results of the components which were developed during that time. Finally a momentum based ACS configuration was chosen. A single fixed momentum wheel and single torquer as actuators, star and sun sensors as sensing devices and two microcomputers as controllers, see fig.1. All used units are "self-made", utilizing commercial components for cost reduction. (Unfortunately it is not yet possible to fly our own developed wheel, because of the GAS safety requirements.)

2.1 Fixed Momentum Wheel (FMW)

The primary function of the Fixed Momentum Wheel is to stabilise the satellite in its roll and yaw axis by the gyroscopic effect and to control the satellite in its pitch axis by wheel acceleration and deceleration (reaction torque). A fixed momentum wheel type DR 50-2 (Teldix) is being used. It is oversized but it was available for a "special price".

2.2 Wheel Drive Electronic

As the wheel motor torque is proportional to the motor current, the main function of the WDE is to control the motor current.For acceleration a positive motor current is fed into the motor, derived from the main power supply. For deceleration no current is supplied, so that a negative reaction torque is provided, due to the friction of the wheel bearing. The WDE output current is linear to the input voltage and limited to 0,5 A, for avoiding damage to the motor coils. The torque control signal U_{stell} 0-5 V is fed from the MPU to the WDE. Therefore the motor torque is proportional to the control signal,see fig. 2.

2.3 Microcomputer

The closed loop pitch control and the open loop roll/yaw control are each based on a microcomputer unit (CPU). It is an 8 bit CMOS single chip microcomputer of the type HD63701YOF (Hitachi) and contains 11 k bytes of PROM, 256 bytes of RAM, serial communication interface and 53 parallel input/output pins.

Pitch CPU: It is collecting and distributing the following signals:

Input:
- corrected FMW, tacho signal
- solar sensor panel signal
- star sensor signal
- pitch mode command from the roll/yaw CPU

Output:- wheel torque control signal to WDE U_{stell}

- reset signal to the star sensor
- status information to the roll/yaw CPU

Roll/yaw CPU: It is actually the onboard data handling computer but also responsible for coordination and control of the pitch axis reorientation maneuver.

2.4 Sunsensor (SS)

There are two options for sensing the sun direction.

1. Two small solarcells, mounted on the surface of the outer shell with an angle of 90° or 135°. No pitch error is provided if the satellite surface (in the case of 90°) or the satellite edge (in the case of 135°) is pointing towards the sun.
2. The pitch error signal can be sensed by comparing the output voltage of the relevant solar panel.

2.5 Starsensor (STS)

There are two star sensors used, one for pitch and the other for roll/yaw attitude sensing. The STS is based on a 288 by 388 pixel CCD chip camera, and an 8 bit micro-computer unit and these provide a single axis measurement. The image of the star configuration taken at the time t_0 being reduced to a row of 288 pixel. The existence of at least one star is presented by logical 1 or else 0. The drift angle is provided by shifting

the raw from the image taken at the time t_n against the first one until correlation is achieved. The STS can be operated in the following modes:

- Rate integration mode which provides the drift angle (φ) between the time t_0 and t_n. The results are ready after 220 ms. Using a 20 mm lens gives a 20° field of view and maximum allowable satellite angular rate of 45°/s (7.5 rpm).
- Rate mode, whereby each image is compared with the previous one (t_n, t_{n+1}). Dividing this by the time interval provides the angular rate. The result is ready after 240 ms and the maximum allowable satellite angular rate is 500°/s (83 rpm).
- A mode which provides φ and $\dot{\varphi}$ in every 440 ms
- A mode which provides the position (one axis) and the size of the biggest star.
- A mode which uses the STS as a camera for attitude determination (by transmitting the star image to the ground station)

The next generation of STS with two axis information is being developed. The use of a 16 bit MCU will reduce the computation time to about 1/5. A drastic reduction in power consump tion can be achieved by not using the TV norm.

2.6 Summary of Components

components	mass [kg]	power [watt]	
- FMW (Teldix)	5.7	2.0	(1000rpm)
FMW (T.U. Berlin)	2.5	≈ 2.0	(1000rpm)
- Torquer	1.0	2.0	
- SS	0.1	0.05	
- STS	0.5	2.0	
- WDE	0.3	0.1	
- CPU +electronics	0.3	≈ 0.2	

3. System Design

The preliminary design of the nominal wheel momentum was based on its effect on pointing error due to a steady roll disturbance torque, assuming a worst case of displacement between the center of pressure (CP) and the center of mass (CM) and a high atmospheric density [1]

$$M_{aer} = m_{aer}\ 0.5\ \rho\ V^2$$

with $m_{aer} = C_d\ F\ d\ \sin\alpha$

gives disturbance torque of $2.61\ 10^{-5}$ Nm. The design pitch pointing error is 0.26 , so:

$$H_g = M_{aer}/\omega_o\ \psi$$

gives the bias momentum requirement of 5 Nms and via:

$$\omega_g = H_g/I_g$$

we get the nominal wheel speed of 460 rpm and the expected nutation frequency of:

$$\omega_n = H_g/(I_x I_y)^{0.5} = 5{,}1\ \text{rad/s} = 48{,}7\ \text{rpm}$$

Wheel momentum saturation/desaturation and reorientation of the momentum vektor is performed by magnetic torquer. The maximum precession rate

$$\omega = BD/H_g = 2{,}22.10^{-4}\ \text{rad/s} = 0{,}76\ \text{deg/min}$$

with torquer magnetic dipole moment of 27.7 Am^2 in a field of $4.10\ T^{-5}$ and wheel angular momentum of 5 Nms.

the expected satellite spin/despin rate with the torquer in a field of $2.10\ T^{-5}$ is:

$$\dot{\varphi}_s = BD/I_y - I_g = 5{,}2.10^{-4}\ \text{rad/s}^2 = 0{,}29\ \text{rpm/min}$$

and with $I_s/I_g = 11$ follows the wheel acceleration/deceleration rate of 3.2 rpm/min.

4. Pitch Control

4.1 Requirements and Design Philosophy

According to the already mentioned general requirements here high flexibility means that the control system should be capable of performing different kinds of slew maneuvers, i.e.

- for positioning the roll/yaw one axis STS in any desired direction for pitch axis reorientation
- for positioning the torquer for wheel momentum desaturation
- for earth observation purposes.

To achieve this high degree of flexibility a microcomputer- based realisation is preferred over analog solutions. Further on, the system should contain as few components as possible with preference for simple ones over highly sophisticated but less reliable ones. The control strategies should be robust and simple and should not contain any highly sensitive parameters.

Based on these considerations, nonlinear switching control laws have been adopted for the current design of TUBSAT, that proved to be robust and simple. Minimum power consumption is guaranteed because the drive of the FMW is switched with minimum losses. This is clearly an advantage over linear solutions. As can be seen in the functional block diagram (fig. 3) the pitch control is organised in a cascade configuration.

The inner loop realises the control of the angular velocity of the FMW (RPM control) while the outer loop controls the pitch angle. This scheme stabilises the momentum of the satellite even in cases of failure in the outer control loop. In these situations the outer loop is disactivated and the momentum stabilised by controlling the angular velocity of the FMW in the inner loop (mode 0). Modes 1 and 2 indicate the activation of the sun- and starsensor respectively.

In the following a mathematical model of the satellite - FMW system, the functional principles of the RPM- and pitch control and some aspects of the actual implementation are described. The section concludes with the presentation of some results that have been recorded from our experiments with a laboratory prototype of TUBSAT.

4.2 Mathematical Model of the FMW-Satellite System

In the following it is assumed, that only the momentum in the direction of the pitch axis is different from zero. In this case Euler's rotational law for rigid bodies can be formulated [1] :

$$d/dt\, H = M_{dist} \;,\quad H = I_y \omega_s + I_g \omega_g \qquad (1)$$

where
- H : momentum in direction of the pitch axis
- M_{dist} : torque that is induced by the disturbances (atmospheric forces etc.)
- I_y, I_g : moments of inertia of the satellite and the FMW in the direction of the pitch axis respectively
- ω_s, ω_g : angular velocities of the satellite and FMW resp.

From (1) it follows that

$$I_y \dot{\omega}_s = - I_g \dot{\omega}_g + M_{dist} \qquad (2)$$

The dynamics of the FMW can be described [1] as

$$I_g(\dot{\omega}_s + \dot{\omega}_g) = M_{drive} - M_{fr}$$

- M_{drive} : torque of the drive unit of the FMW
- M_{fr} : torque that is induced due to the wheel bearing

Combining with (2), it follows

$$I_1\dot{\omega}_g = M_{drive} - M_{fr} - K_1 M_{dist} \qquad (3)$$

where $K_1 = I_g/I_y < 1$ and $I_1 = (1-K_1)\,I_g$

In conclusion, with φ_s denoting the pitch angle and keeping in mind that $I_g = I_1/(1-K_1)$ we have the mathematical model

$$\dot{\varphi}_s = \omega_s \qquad (4a)$$
$$I_y\dot{\omega}_s = -1/(1-K_1)\, I_1\dot{\omega}_g + M_{dist} \qquad (4b)$$
$$I_1\dot{\omega}_g = M_{drive} - M_{fr} - K_1 M_{dist} \qquad (4c)$$

The structure of the system model is illustrated in the functional block diagram see fig. 3 (1/s denotes integration with respect to time).

4.3 RPM Control

In principle, the angular velocity of the FMW can be controlled using a simple on - off switching law for the WDE. Define the error

$$e_\omega := \omega_{gr} - \omega_g \qquad (5)$$

ω_{gr} being a desired value that is assumed to be nearly constant (slowly varying). Then it follows :

$$\dot{e}_\omega := -\dot{\omega}_g \qquad (6)$$

The disturbance M_{dist} and the friction M_{fr} are assumed to be nearly constant in time with

$$M_{fr} > 0 \quad \text{and} \quad -M_{fr} - K_1 M_{dist} < 0 \qquad (7)$$

Defining the control M_a

$$M_a = \begin{cases} -M_{fr} & \text{when} \quad e_\omega < 0 \quad \text{(drive off)} \\ (M_{drive} - M_{fr}) > 0 & \text{when} \quad e_\omega > 0 \quad \text{(drive on)} \end{cases}$$

then it follows from (3) and (6)

$$\dot{e}_\omega = (K_1 M_{dist} - M_a)/I_1 \qquad (8)$$

The phase trajectories of $\dot{e}_\omega$ and e_ω can be seen in fig. 4, the arrows indicate the direction of movement. Stabilty for $e_\omega = 0$ is guaranteed for all possible initial errors $e_\omega(t_0)$, provided that (7) holds, which is true for the expected disturbances.

4.4 Pitch Control Loop

As in the case of RPM control a nonlinear switching control law has been selected for the pitch control. Neglecting the disturbance M_{dist} and substituting (4c) into (4b) gives

$$\dot{\omega}_s = 1/(1-K_1)I_y \quad (M_{fr} - M_{drive}) \tag{9}$$

Setting $M_a = (M_{fr} - M_{drive})$ and dividing (4a) by (9) it follows

$$d\varphi_s / d\omega_s = (1-K_1)I_y\omega_s / M_a \; ,$$
$$M_a \, d\varphi_s = (1-K_1)I_y\omega_s \, d\omega_s \tag{10}$$

Since the switched torque M_{drive} is constant between two switching time points and the friction M_{fr} is nearly constant, integration of (10) gives

$$M_{ai}(\varphi_s(t) - \varphi_s(t_i)) = (1-K_1)I_y / 2 \; (\omega_s^2(t) - \omega_s^2(t_i)) \tag{11}$$

where t_i denotes the ith switching point and M_{ai} denotes the constant torque between the ith and (i+1)th switching point.

Now define the error of the pitch control to be

$$e_\varphi(t) := \varphi_s(t) - \varphi_{sr} \; , \quad \varphi_{sr} = \text{const.} \; , \; \dot{e}_\varphi(t) = \omega_s(t)$$

where φ_{sr} denotes the desired pitch angle. Substituting this into (11) gives

$$e_\varphi(t) - e_\varphi(t_i) = (1-K_1)I_y / 2M_{ai} \; (\dot{e}_\varphi^2(t) - \dot{e}_\varphi^2(t_i)) \tag{12}$$

This is a family of parabolas depending on $e_\varphi(t_i)$, $\dot{e}_\varphi(t_i)$ and M_{ai} and describes the phase trajectories of the pitch error e_φ and its time derivative $\dot{e}_\varphi$. The possible values for M_{ai} are M_{fr} and $(M_{fr} - M_{drive})$ corresponding to an on - off switching of the FMW, i.e. there are two types of parabolas according to the two possible values of M_{ai}, this is illustrated in the phase-plane, see fig.5. To specify the switching points for M_{ai}, we adopted a simple and familiar control law, see e.g. [2] , namely switching along the straight line

$$\dot{e}_\varphi = -m \, e_\varphi \; , \quad m > 0$$

see fig. 5, that means

$$M_{ai} = \begin{cases} M_{fr} & \text{when} \quad \dot{e}_\varphi(t) < -m \, e_\varphi(t) \; , \\ (M_{fr} - M_{drive}) & \text{when} \quad \dot{e}_\varphi(t) > -m \, e_\varphi(t) \end{cases} \tag{13}$$

As one can see from fig. 5, the stability of the point ($e_\varphi = 0$, $\dot{e}_\varphi = 0$) is guaranteed for all possible initial disturbances $e_\varphi(t_0)$, $\dot{e}_\varphi(t_0)$ (fig. 5 shows one example). It remains to show how the pitch control law interacts with the RPM control. The pitch controller must generate a signal $r(t)$ that causes the RPM controller to switch to the desired M_{ai} of (13). Since the input of the RPM control loop is ω_{gr} (the desired value of the angular velocity of the FMW), $r(t)$ must take on the form :

$$r(t) = \omega_{gr}(t_i) + \quad m_{ai}\, d\tau \; , \qquad t_i < t < t_{i+1} \qquad (14)$$

where $\quad m_{ai} = {}^{M_{ai}}/ I_1 \quad$, see fig. 3.

Therefore, in addition to the algorithm (13) an integrator that performs the integration in (14) is necessary.

4.5 Implementation

The RPM and pitch control laws that were given above in time-continous form have been reformulated in discrete time and implemented with little changes on the MCU. The angular velocity of the FMW is sensed using a standard tacho signal by measuring the time between two succesive edges of the wheel comutation (8 pulses / rev.). So actually the equivalent time-period $T_{ist}(k)$ of the FMW was controlled instead of the angular velocity, but this is only a slight difference. The disturbances due to finite time resolution and commutator noise of the tacho are reduced using a moving-average filter (MA) the effect of which is apparent from fig.6 . With a filter order of eight a reduction of the standard deviation of the disturbance $v(t)$ on the order of $\sqrt{8}$ is achieved (upper curve filtered, lower curve unfiltered).
The on - off RPM control is slightly changed by including additional levels of the torque M_{drive} for small values of the RPM error e_ω, this gives a better performance of the overall control.
The integration in (14) is approximated by a discrete summation of the output of the switching algorithm, the time derivative of e_φ that is needed in (13) is approximated by appropriate differences.
The sampling rate of the RPM control loop depends on the angular velocity of the FMW and ranges from 7.5 ms ($\hat{=}$ 1000 RPM) to 18.7 ms ($\hat{=}$ 400 RPM).
The sampling rate of the pitch control loop is constantly 200 ms .
The circuit-plan of the pitch control loop is depicted in fig. 7.
As can be seen, the starsensor is connected directly to one port of the MCU, while the signal of the sunsensor is preprocessed by IC5, IC6 and A/D (IC2) converted with 8 bit accuracy.
The WDE and tacho are connected to the MCU via a Schmitt trigger (IC1).
The MCU delivers a signal to the watch dog timer every 250 ms; in case of absence of this signal reset of the MCU follows. In this case the MCU immediately measures the tacho velocity and takes this value for the new reference.

4.6 Results

The pitch control unit was tested in a laboratory environment, suspending the TUBSAT prototype satellite using a thin rope. The rope induced a disturbance-torque M_{dist} on the satellite due to its elastic forces. This disturbance is much higher in absolute value than the expected disturbances during an outer space application of the satellite, so that our experiments can be seen as "worst case examples". Fig.8 shows how the satellite follows the sun in different positions during a sun-locked operation. As can be seen, a pointing accuracy of 0.15° is achieved. In fig.9 the effect of an impulse-disturbance during star-locked operation is presented. Here the pointing accuracy is about 0.13°. Finally, an STS pitch slew maneuver of about 4° that is composed of two steps corresponding to two successive images of the starsensor is shown in fig.10.

Acknowledgement

Many thanks to Prof. Dr.-Ing. U. Renner for his valuable ideas on developing and realising this concept.

Nomenclature

I_x, I_y, I_z	Principal moments of inertia plus momentum wheel (0.9632, 1.177, 0.9632 kg.m^2)
I_g	Momentum wheel spin axis moment of inertia (0.1039 kg.m^2)
C_d	Coefficient of drag (2.2)
D	Torquer magnetic dipole moment (27.7 Amm)
B	Geomagnetic induction
d	Displacement between CM and CP (50mm)
F	Satellite characteristic area (0.25 m^2)
V	Satellite velocity (7.7km/s)
H_g	Momentum wheel angular momentum
α	Angle between aerodynamic and pitch vector

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[2] J. Böcker, I. Hartmann, Ch. Zwanzig : Nichtlineare und adaptive Regelungssysteme, Springer Verlag Berlin, Heidelberg, New York etc. , 1986

[3] J.R. Wertz : Spacecraft Attitude Determination And Control, D. Reidel Publishing Company, Dordrecht: Holland/Bosten: USA etc., 1978

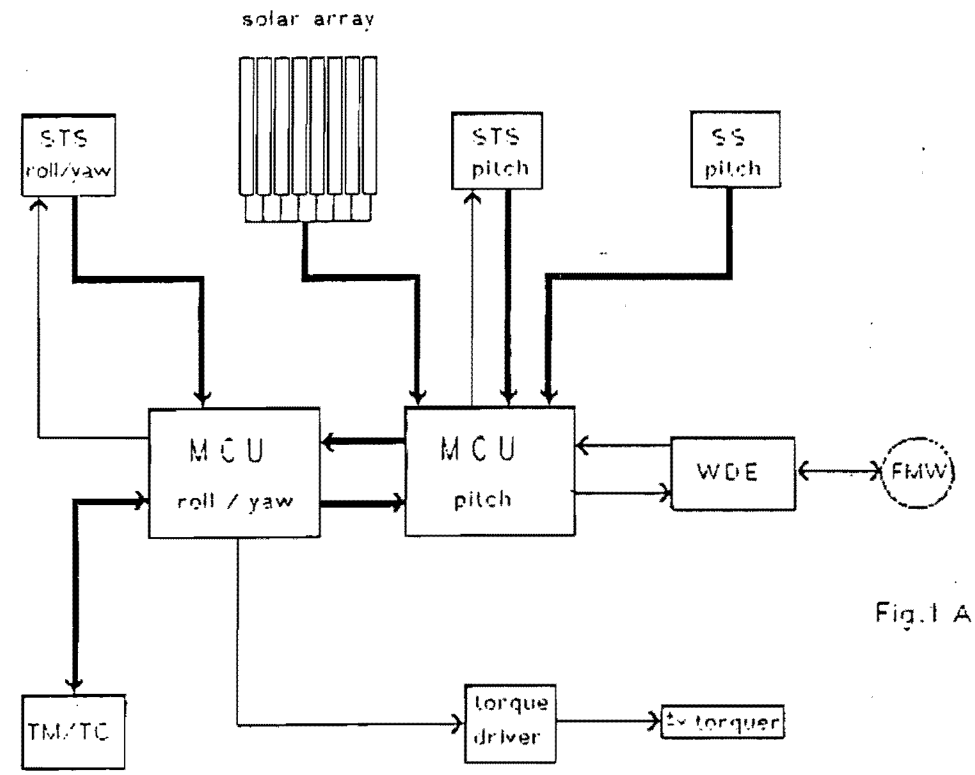


Fig.1 ACS Block Diagram

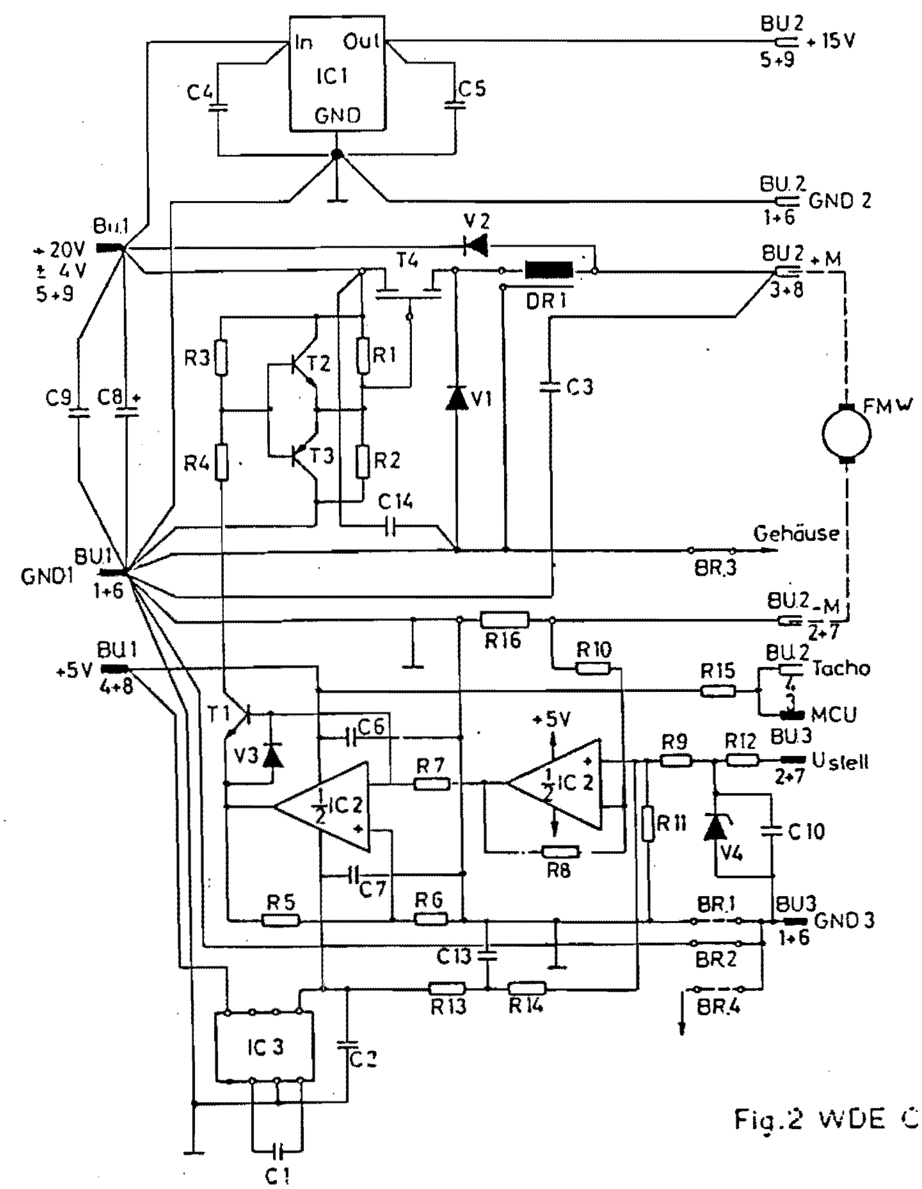
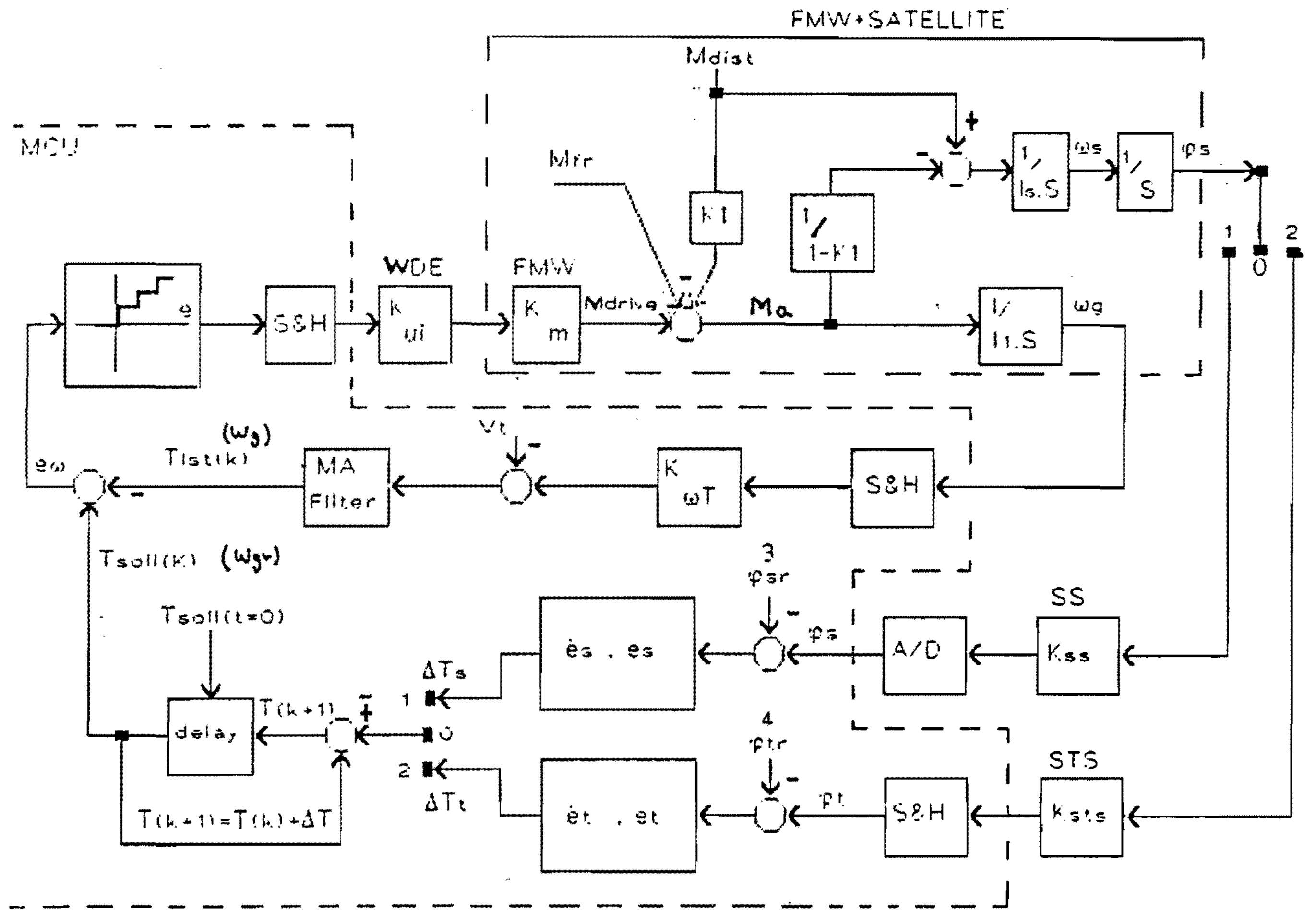


Fig.2 WDE Circuit Diagram



WDE : wheel drive electronic	0 : constant wheel speed mode
FMW : fixed momentum wheel	1 : sunsensor mode
SS : sunsensor	2 : starsensor mode
STS : starsensor	3 : ss pitch maneuver mode
MCU : microcomputerunit	4 : sts pitch maneuver mode

Fig. 3 Functional Block Diagram of the TUBSAT-1 Pitch Control System

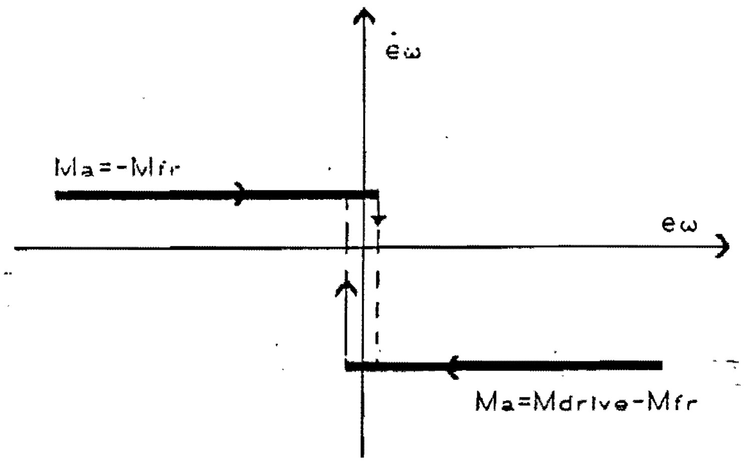


Fig.4 phase plane of RPM-error

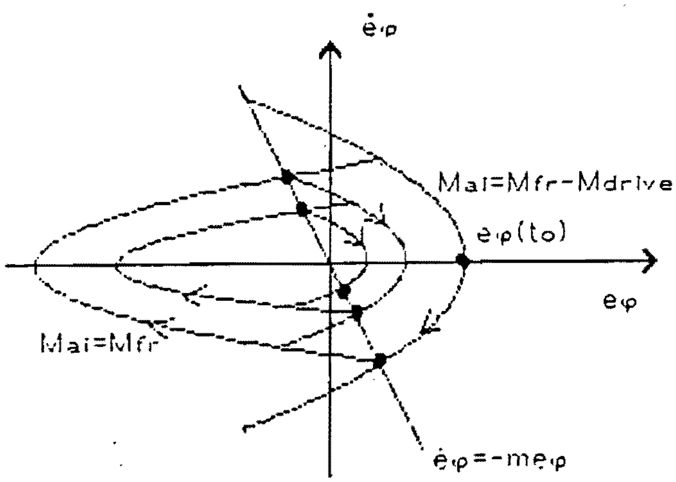


Fig.5 Phase plane of PITCH-error

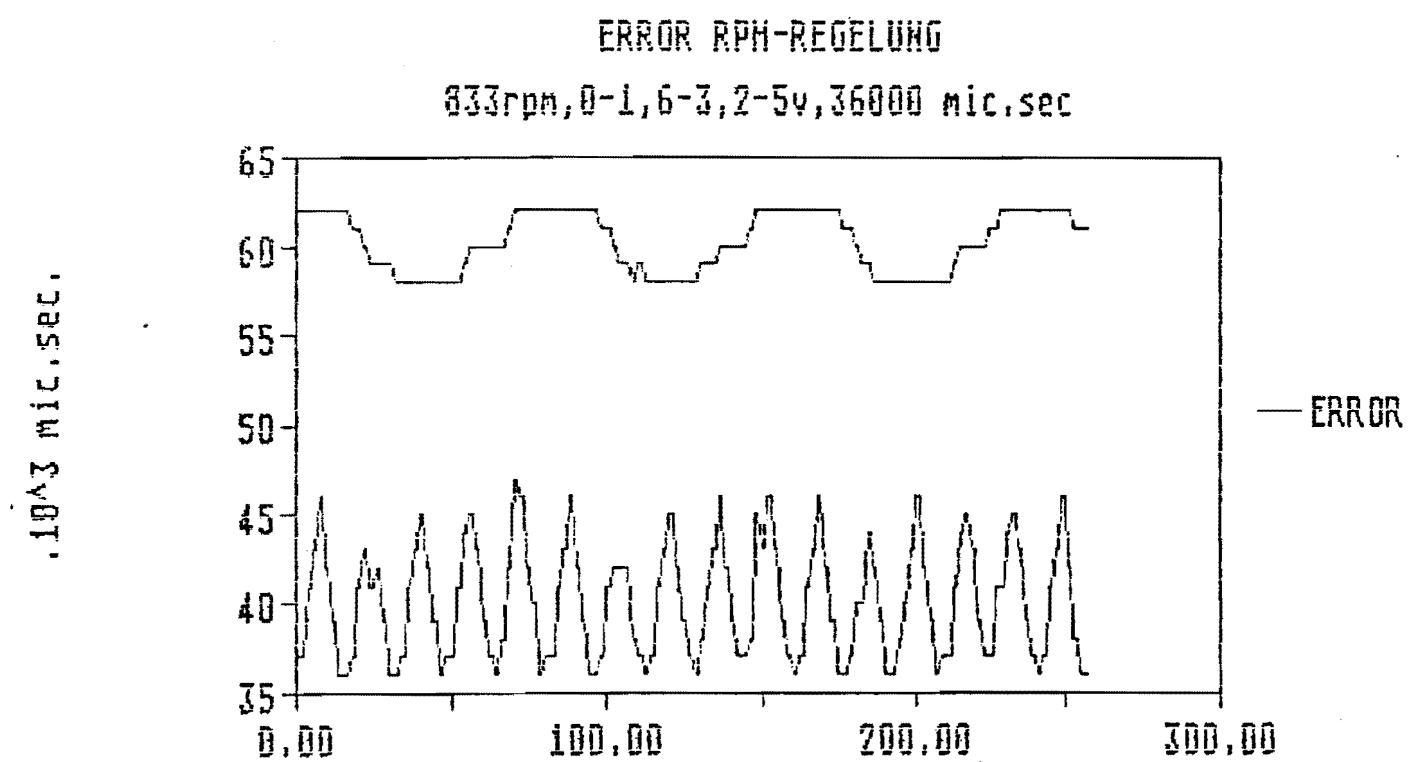


Fig.6 RPM Control

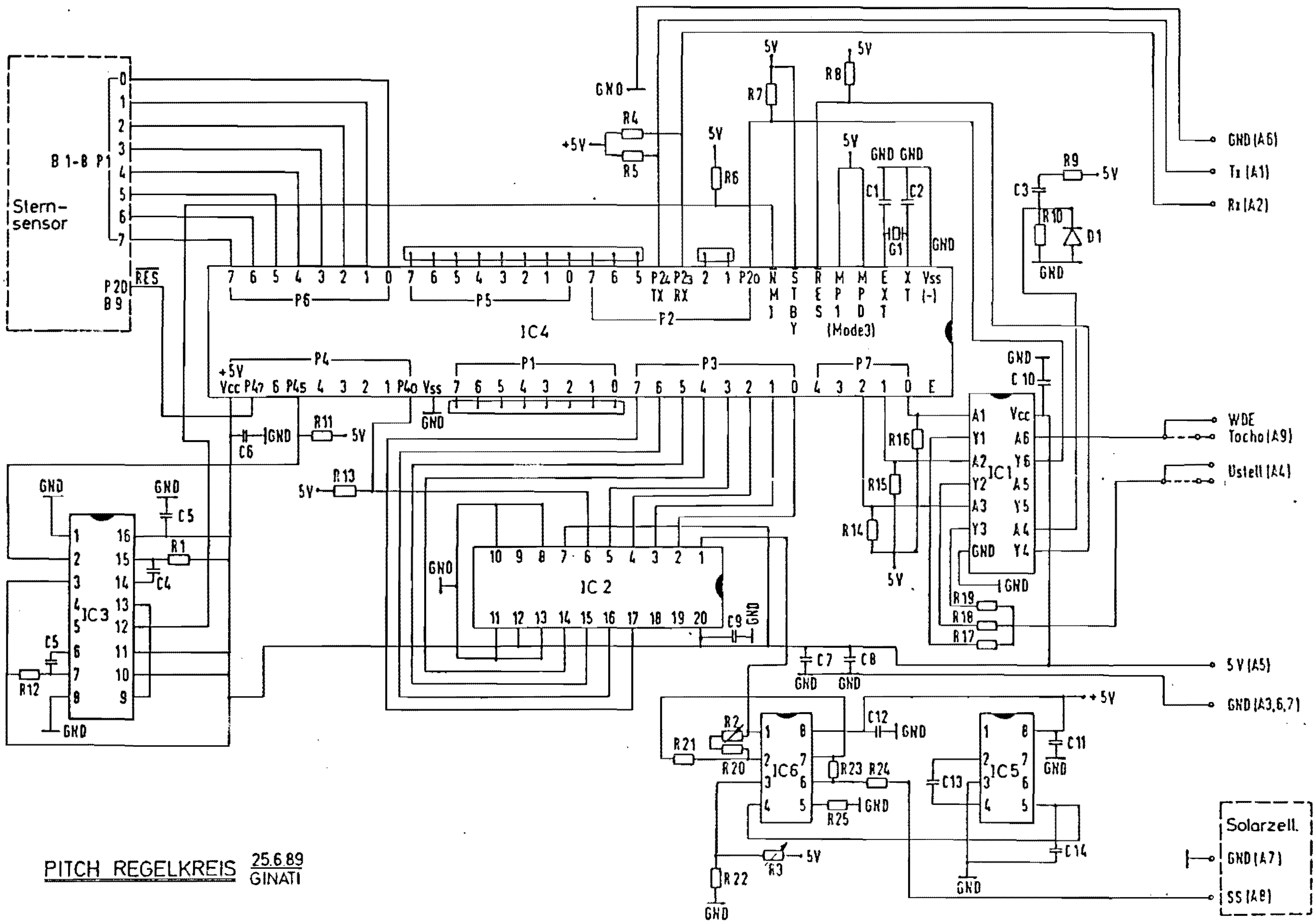


Fig.7 Pitch Circuit Diagram

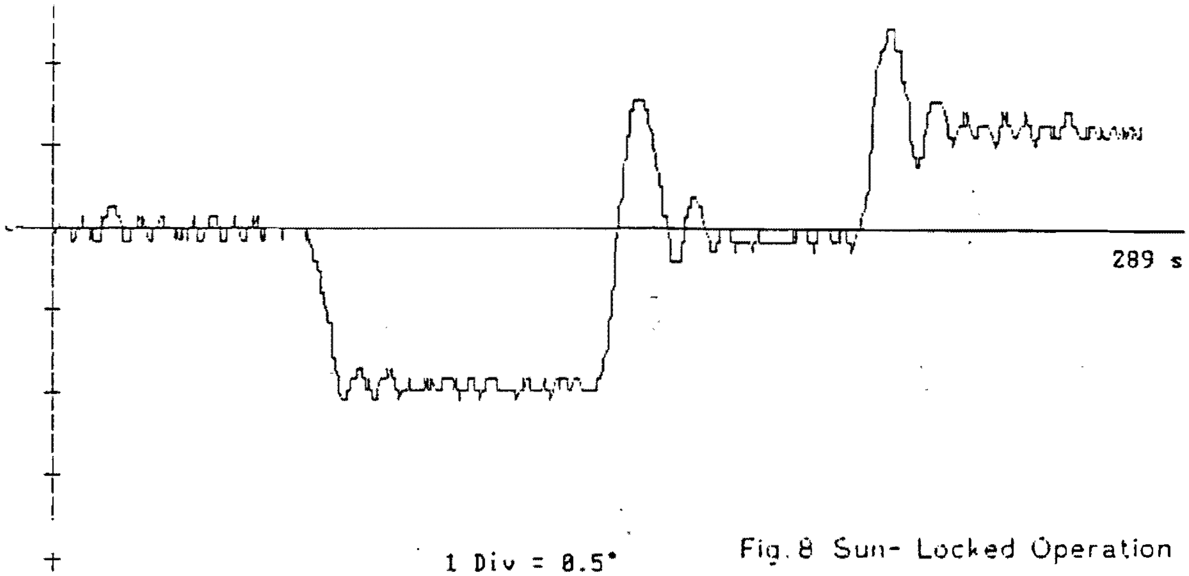


Fig. 8 Sun- Locked Operation

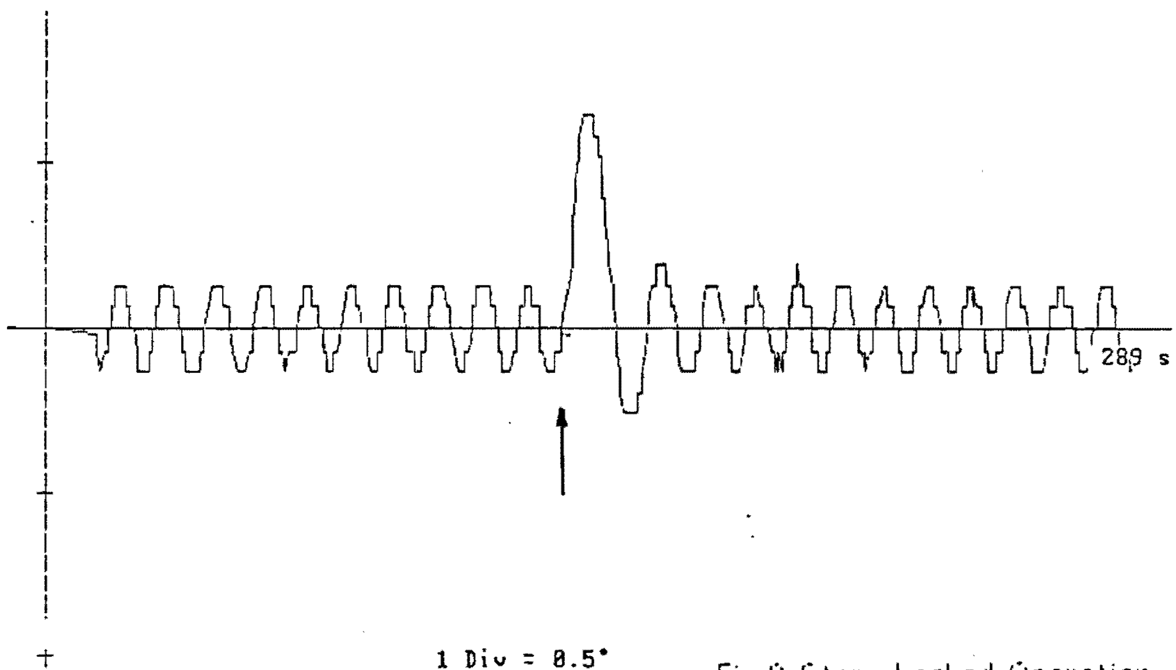


Fig. 9 Star- Locked Operation

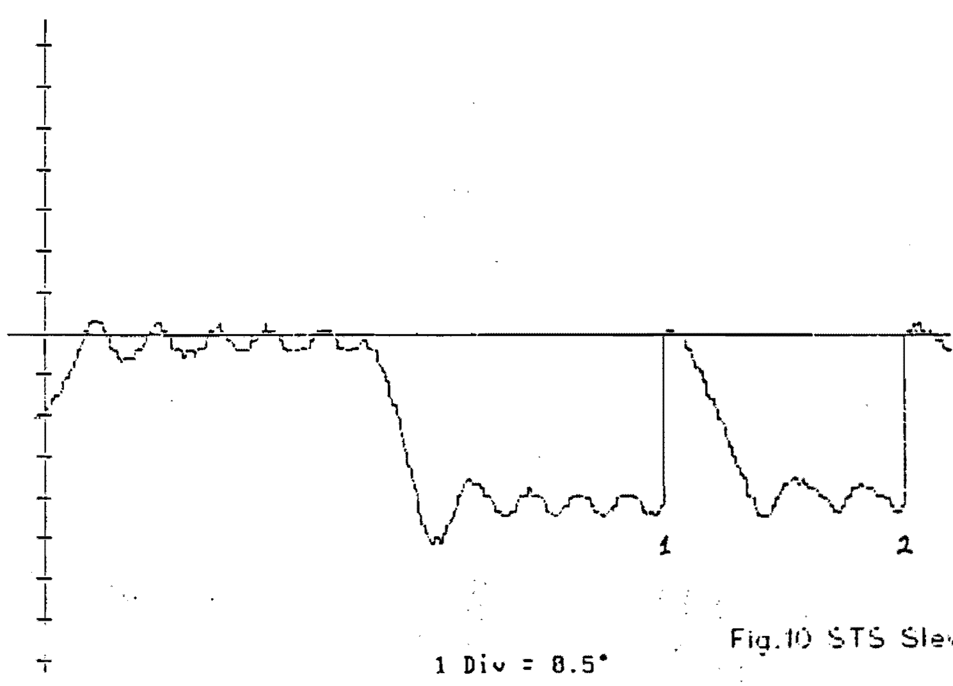


Fig. 10 STS Slew Maneuver