BREM-SAT Attitude control at low altitudes

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The German University satellite BREM-SAT (scheduled for launch in early 1993) carries two experiments which require attitude control down to 150 km altitude and aerodynamic stabilisation between 150 and 100 km altitude. These contradicting requirements need new ways to change the satellite's attitude and to keep it stable and controlled at very high disturbance torque levels. Complex numerical attitude simulation has shown the feasibility to maintain the required attitude with a momentum wheel and a single torque coil down to 150 km when optimized algorithms are used. To achieve the aerodynamic stabilisation, the momentum wheel has to be ejected and flaps must be deployed just before loosing attitude control.

INTRODUCTION

Small satellites launched by the Space Shuttle with a GAS (Get Away Special) container have typically short lifetimes at solar maximum. The orbit decays from 300 km down to 200 km within a few weeks (4-6 weeks). At an altitude of about 200 km, usually no further experiments will be carried out and the satellite will burn up in a few days. For scientists, this low altitude offers a unique chance to investigate some effects related to the free molecular flow and the transition region to continuum flow.

While performing experiments at low altitudes without a re-entry capsule, two problems arise. First, the data have to be transmitted to ground stations; additionally, a required attitude has to be maintained. This paper deals (only) with the second problem which is enforced by two completely different attitude requirements of the last two experiments.

When reaching 160 km altitude, already four experiments have been carried out onboard of BREM-SAT [1]. Still there are two experiments, one of them measuring the gas-surface interaction, the other investigating the upper reentry flow conditions. The gas-surface interaction is determined by means of a floating solar panel connected to a balance, thus directly measuring the force on the panel. This experiment requires an attitude with the pitch axis perpendicular to the orbital plane and a slow rotation about this axis. It is obvious that a certain aerodynamic force is necessary to be resolved by the balance; on the other hand, strong forces (and therefore, moments) will destabilize the attitude control system. It should be noted at that point, that only electrical actuators can be used; i.e. a momentum wheel and a magnetic torquer.

The last experiment measures the temperature and pressure distribution at 120 km and less [2]. In fact, receiving the last results will depend on the ground stations positions. The satellite will burn up at app. 60 km, but a communication black-out due to ionisation will occur earlier. It is easy to understand that - due to the rapidly increasing forces - only aerodynamic stabilisation, with the pitch axis in flight direction, is applicable in this phase. This is not possible with a momentum wheel located like in BREM-SAT - therefore it will be ejected through the GAS- adapter.

Two major questions have to be answered by our simulations:

- How long will the satellite withstand the aerodynamic moments during the gas-surface experiment?
- Will it turn the right way after the momentum wheel is ejected?

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MATHEMATICAL MODEL

The fundamental equations describing the attitude motion of a momentum biased satellite are well described in Wertz, Spacecraft Attitude Determination & Control [3]. Euler symmetric parameters (quaternions) are used to evaluate the motion in inertial space. However, Euler angles are used to describe the motion in two different coordinate systems, the body system and the so-called orbital system. Our "target" vector is the orbital system, where the satellite's pitch axis has to be aligned to the orbit normal vector. In Fig. 1 these two coordinate system are shown; please note, that the pitch axis is equivalent to the $+Z_{Body}$ axis and the momentum wheel spin axis. The torquer is located in the $+X_{Body}$ axis.

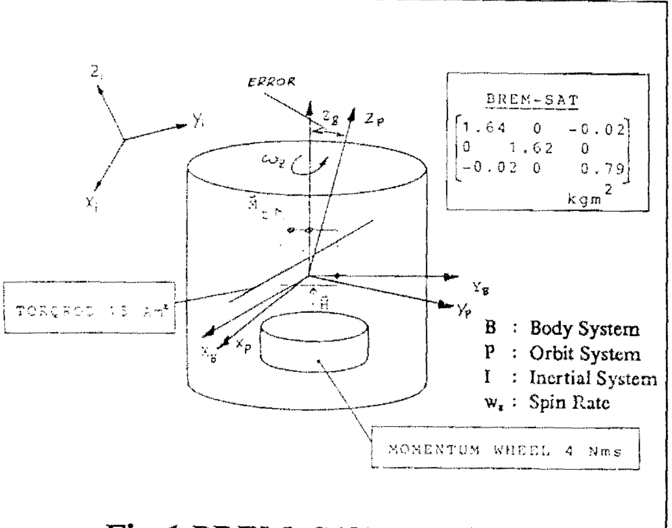


Fig. 1 BREM-SAT coordinates

To simulate the attitude motion, evaluation of environmental forces and moments is necessary. CIRA-86 (Cospar International Reference Atmosphere) has been adopted as atmospheric model, taking into account all variables that may influence the atmosphere as AP (planetary magnetic index), F10.7 (solar radiation at 10.7 cm), solar time etc. This model can be used down to 90 km altitude [4]. For control torque calculation, the earth magnetic field model IGRF-1985 (International Geomagnetic Reference Model) [5], extrapolated to 1993, is used.

One of the most important variables related to both attitude and orbit dynamics is the implementation of drag and lift coefficients, C_D and C_L. Simplified solutions or estimates are not applicable in this case. Instead, Monte-Carlo simulations have been made to approximate these coefficients and the center of pressure. Although the coefficients depend on the altitude (See fig. 2), average values have been used to reduce the effort (which still depend on the "angle of attack").

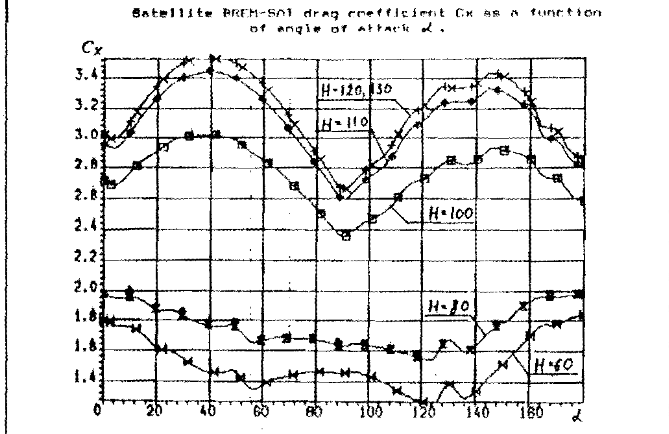


Fig. 2 C_D coefficient vs. angle of attack

All simulation software has been written in "C" and can be run on a PC or a workstation.

MOTION WITHOUT CONTROL

Since the aerodynamic torque is by far the largest disturbance torque, attitude motion is mainly caused by the density profile and the center of mass (COM) to center of pressure (COP) offset. The COM is +255 mm, as required by NASA, whereas the COP has been determined at +261 mm at nominal attitude. The density profiles for various altitudes are shown in fig. 3; variations due to the eccentricity of the earth and the orbit are superimposed by day/night fluctuations. The disturbance moments range from $3.6*10^{-6}$ Nm at 300 km to $3.7*10^{-4}$ Nm at 150 km (average values). At a single orbit, the satellite will perform an elliptical motion in inertial space. At the dayside and at lower altitudes, the angular momentum precession is "faster" than at the nightside or at higher altitudes. Therefore, the motion is not cyclic and needs to be corrected. Since the satellites spin axis has to be aligned

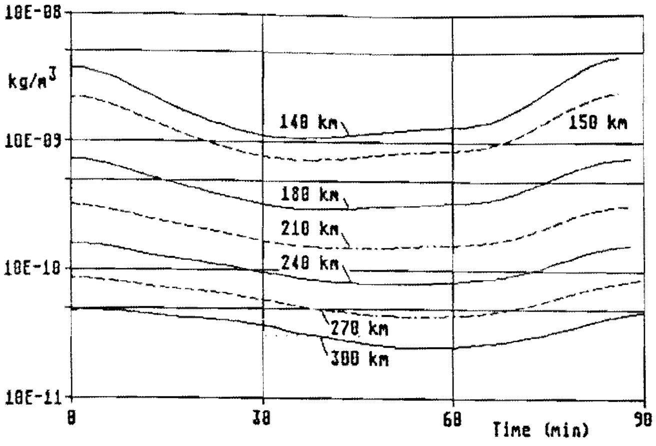


Fig. 3 Density profile at different orbits

to the orbit normal, another effect is more important at high altitudes. The earth's gravitational field is not spherical, causing the ascending node of the orbit to move retrograde at -7.5°/day. Not only the satellite, but the target vector - orbit normal - moves. This is depicted in fig. 4, showing the rotation about the X and Y-axis without control. On the left side of fig. 4, this motion is shown with respect to the orbit (target) system, on the right side the same motion is demonstrated in inertial space. It can be seen easily, that orbital motion effects the attitude error. No rotation about the +Z-axis has been involved in this simulation. Without control, the motion appears to be smooth and has almost no nutation.

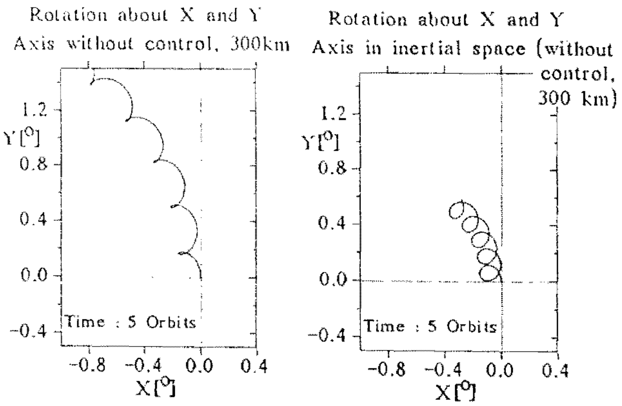


Fig. 4 Motion without control. Left: orbit coordinate system, right: inertial space

CONTROL TORQUES

As indicated above, just a single torque coil is used to compensate precession and target vector motion. In addition, only every 100 seconds the control loop can be activated. Since the satellite rotates slowly, torque pulses have to be timed correctly with respect to the attitude error. The torquer (produced by ITHACO) generates a magnetic moment of 15 Am^2, which creates $4.5*10^{-4}$ Nm control torque with 30000 nT earth magnetic field. The control moment is perpendicular to the torquer axis and the magnetic field vector and must therefore be within the Y/Z_{Body} plane of the satellite. Only the portion in Y axis compensates the precession, whereas the Z axis component affects the angular rate of the satellite. If the angular rate exceeds the range from 0.07 to 0.13 RPM, it is corrected by changing the speed of the momentum wheel.

At an early stage, the control algorithms had been rather simple. Whenever the attitude error is greater than 0.1° and lies within $\Delta = \pm 20^0$ to the Y-axis, the torquer is activated. The pulse time is determined by taking into account a fixed compensation rate of k= 0.64°/min. These two variables, k and Δ, could be optimized with respect to the average error, the root mean square error or the energy used by the torquer. However, this optimization is only for one altitude, and simulation has shown that control is lost at about 180 km altitude. Since this would not have fullfilled the requirements of the gas-surface experiment, further investigation have been made, leading to a adaptive concept. The k-variable is determined by actual magnetometer measurement. Then, k is used to calculate the necessary angle Δ, taking into account the attitude error and the angular rate. Instead of activating the torquer directly, the calculated torquer-on and -off times are stored in registers, leading to much more precise pulse timing than before.

In fig. 5 the function of the adaptive control loop is demonstrated. An initial error of 1.5° about the X-axis is preset at T_0 in a 300 km

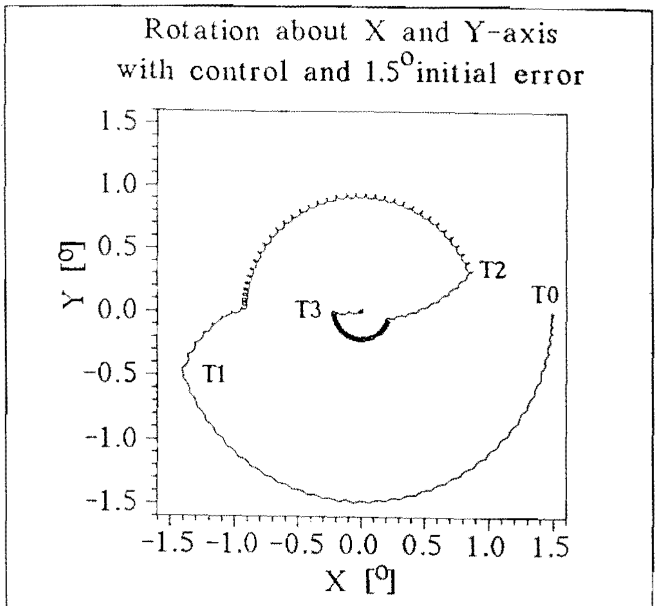


Fig. 5 (see text for explanation)

orbit. Due to the slow rotation, this error moves on a circle until the torquer is in the right position. At T_1 (4min 15sec) the torquer is activated. Only 0.6° error can be compensated, because the torquer-on time is limited to 50 seconds. Besides, a slight nutation with 0.005° half cone angle is introduced. At T_2 (9min) and T_3 (13min 40sec) the rest error is compensated. The residual error is less than 0.01° when the simulation ends after 16min 40sec.

For a long-time simulation the average error (0.12°) is significantly higher, because the control loop is only active when the error exceeds 0.1°. Fig. 6 shows the rotation about X and Y-axis and the torquer pulses over the mission time of 10 orbits (300 km). The torquer is activated approximatly 1.5% of this time, yielding to an average power consumption of 30 mW. As mentioned above, the geomagnetic field portion along the pitch-axis affects the satellites spin rate, which has to be corrected with the momentum wheel. This is depicted in fig. 7, showing that the wheel has 20 RPM more at the end of the simulation. For a longer time, desaturation might be necessary, but until now this algorithm has not been implemented.

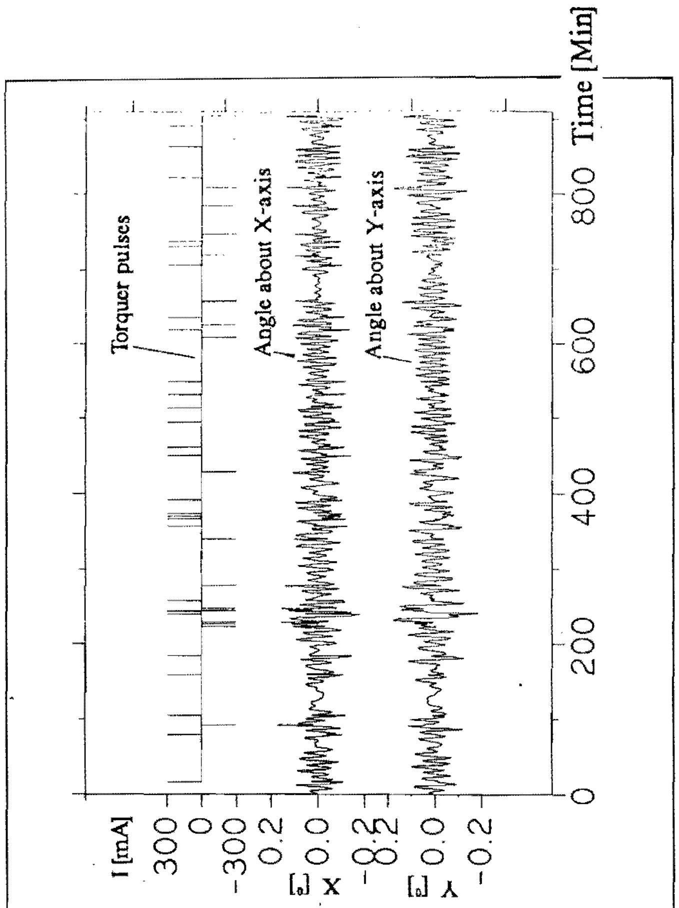


Fig. 6 Long-time simulation

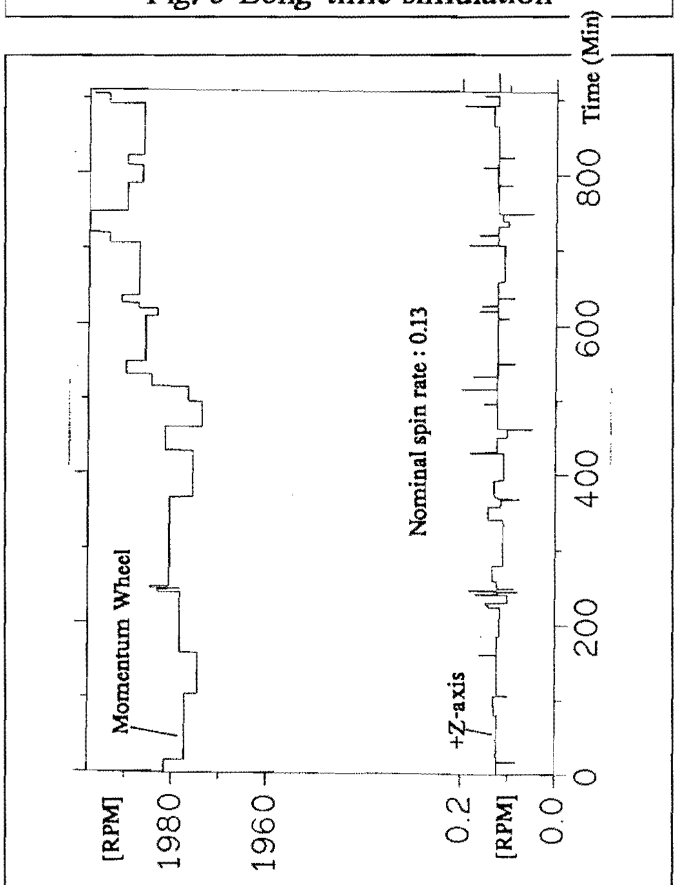


Fig. 7 Pitch and wheel rate

MOTION AT LOW ALTITUDES

Reaching lower altitudes, the torquer-on time increases rapidly due to the increasing aerodynamic moments. At 150 km altitude (semimajor axis = 6428.16 km), the remaining lifetime of BREM-SAT lies between 300 and 400 min., depending on the solar activity. The actual altitude, measured from the earth's surface, still varies more than 22 km, causing disturbance peaks at the lower altitude. The gas-surface experiment requires a minimum force of 0.01 N, which is equivalent to 0.04 N acting on the whole satellite. One particular simulation has been selected to analyse the results. It starts at 150 km altitude at perigee with an orbit eccentricity of 0.002. Fig. 8 shows that almost four orbits are completed before the satellite does its re-entry, and fig. 9 shows the force acting on the satellite. The first opportunity to measure the gas-surface interaction is given at T=80 min. (Fig. 9), if the satellite fullfills the attitude requirement. In the selected simulation, the desired attitude is met within 10°. Other simulations with different initial orbit parameter had shown, that there is at least one chance to measure the gas-surface interaction, because the necessary minimum force is not strong enough to destabilize the satellite. It has been defined, that the attitude control is terminated, if the attitude error reaches 40°, which happens two hours after the first gas-surface measurement in our example simulation. With that large error, measurements are no longer possible and a total loss of the attitude control becomes imminent.

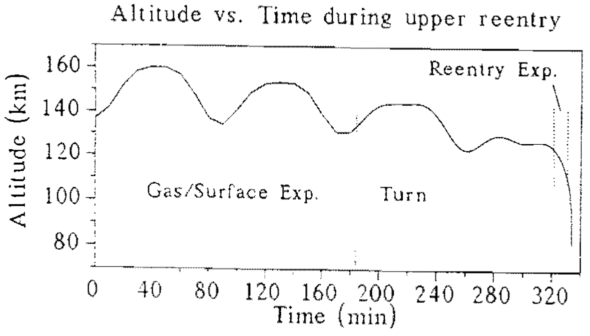


Fig. 8

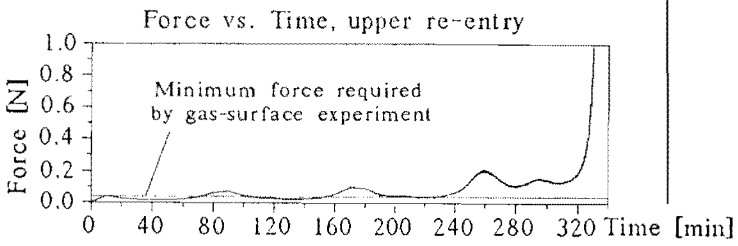


Fig. 9

AERODYNAMIC STABILISATION

The last experiment, upper re-entry measurements, requires the pitch axis (+Z-axis) to be aligned with the flight vector between 120 and 100 km altitude. At these low altitudes, aerodynamic stabilisation seems most favorite because the rapidly increasing forces are used to stabilize the satellite. On the other hand, aerodynamic stabilization requires the center of mass to be in front of the center of pressure. Thus normally flaps are used to generate sufficient stabilization. Since BREM-SAT has been designed to minimize the COP-COM offset, flaps have to be deployed for aerodynamic stabilisation. Furthermore, the angular momentum of the wheel will not allow aerodynamic stabilization. Due to this reason, the momentum wheel has to be removed from the satellite. Fortunatly, the ITHACO-wheel fits perfectly through the GAS-adapter of the satellite, as demonstrated in fig. 10. During launch and in orbit, the wheel is fixed by a central bolt. This bolt (and all cables) is cut by a pyrotechnic bolt-cutter, and a spring pushes the wheel through the adapter. This maneuver has two effects: first, 95% of all angular momentum is removed within a fraction of a second; second, the center of mass is shifted in positive Z-axis direction and is now in front of the COP. Until now, only simulations

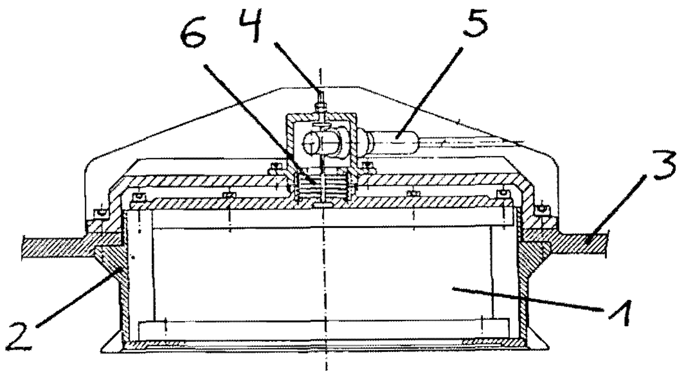


Fig. 10 Momentum wheel ejection mechanism

(Courtesy of OHB-SYSTEM)

1) *Momentum Wheel*
2) *GAS adapter*
3) *Satellite baseplate*
4) *Central bolt*
5) *Pyrotechnic bolt cutter*
6) *Spring*

Fig. 11 Undamped oscillations after momentum wheel ejection (see fig. 8)

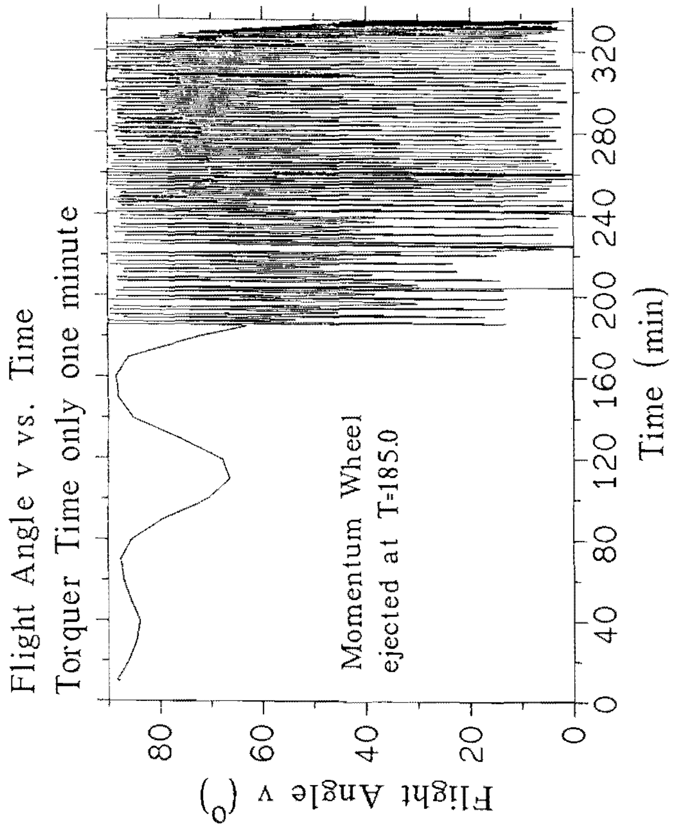
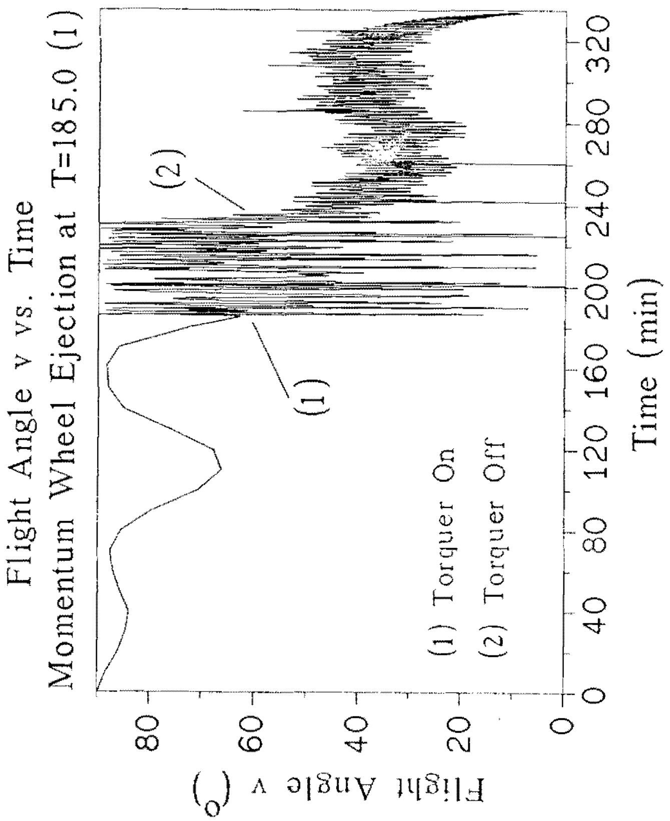


Fig. 12 Oscillations damped by activating the torquer



without flaps have been done, because new C_D and C_L values are necessary. Without flaps, the satellite turns its pitch-axis (+Z-axis) in flight direction after 30 seconds, but this motion is an undamped oscillation. Energy dissipation with a nutation damper might decrease the oscillation, but is not possible since accomodation volume is no more available. The increasing forces during re-entry reduce the amplitude, but not fast enough. Fig. 11 shows the results of the selected simulation without flaps and internal damping. At T=185 min. (compare with fig. 8) the attitude error exceeds 40°, and the momentum wheel is ejected. At that moment, the satellite has an altitude of approximately 130 km. Fig. 11 shows the flight angle, which is the angle between Z-axis and flight vector. Due to sign ambiguity, only values between 0 and 90° are represented (0° might mean as well 180°, but it has been checked). At T=325 min., the aerodynamic forces reduce the flight angle oscillations, but this time is to late to perform the re-entry experiment. Looking for new solutions, we activated the torquer for 50 minutes after the momentum wheel has been ejected (See fig. 12). Since the torquer is mounted in +X direction and the angular momentum of the satellite is comparably small, the X-axis is aligned to the geomagnetic field. Although the field is varying, it is directed mainly in south-north direction. The main effect of activating the torquer and keeping the X-axis (The axis with the highest moment of inertia) to south-north direction is some additional stabilisation, which can be seen when the torquer is switched off at T=235 min (Fig. 12). After that, the flight angle remains in the region 20-40°, which is an improvement compared to fig. 11. Again, the reduction of the flight angle can be seen; in that case, it occurs earlier.

SUMMARY

Performing experiments at low altitudes requires extensive attitude analysis and simulation. Even if no thrusters can be used, attitude control is possible at high disturbance torque levels if appropriate control algorithms are used. Numerical simulation is the most favorable tool to develop these algorithms and to demonstrate its feasability. Thus, it has been shown that the gas-surface experiment of BREM-SAT can be performed although the torque levels are unusally high. To simulate the motion during the upper re-entry, some improvements have to be integrated in our simulation. Still first results have shown that the turn-maneuver can be performed and oscillations can be damped with the magnetic torquer.

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