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Extremely compact secondary mirror unit for the SOFIA telescope capable of 6-degree-of-freedom alignment plus chopping

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ABSTRACT

SOFIA is a 2.5-m telescope to be carried on a special Boeing 747 for airborne observations at about 15'000 m. The paper describes the main features of the secondary mirror unit. The SOFIA secondary mirror needs active control for alignment along five degrees of freedom as well as for very fast chopping with a frequency up to 20 Hz. Moreover the general optical concept and the housing of the telescope inside a Boeing 747 have required the design of a very compact mechanism: indeed while the secondary mirror has a diameter of 350 mm the entire height of the secondary mirror unit (including the mirror) cannot be greater than 300 mm, which makes the SOFIA design much more compact than any other similar project.

The objective is achieved by a very tight integration between a novel hexapod mechanism, in charge of tilt offsets and alignment along 3 axes, and a fast chopping mechanism based on advanced flexure structure technology. In the hexapod mechanism (which is in fact capable of 6-dof), the six linear actuators are arranged in an original geometry in order to leave as much space as possible to the overlying chopping system. Also, the actuators' "hinges" are here materialized by flexure elements. Three motorized levers are linked by flexure elements to the mirror isostatic interface as well as to a reaction ring for compensating angular momentum, which is mechanically driven together with the mirror. This a major difference from other designs (e.g. Keck or VLT) where the compensation mass is driven and controlled separately. The SOFIA solution obtains thus various advantages in term of used volume and has a simpler control system. Various details of the chopping mechanism are provided in the paper. Simulation preliminary results are also given.

Keywords: Secondary mirror, active secondary unit, chopping, flexure structures

1. INTRODUCTION

The USA and German aerospace agencies NASA and DARA are jointly developing the Stratospheric Observatory For Infrared Astronomy (SOFIA). A Boeing 747-SP aircraft will carry a 2.5-meter telescope designed to make sensitive infrared measurements of a wide range of astronomical objects. It will fly at and above 12.5 km, where the telescope collects undisturbed radiation in the wavelength range from 300 nanometers to 1.6 millimeters. The telescope has some very demanding environmental and reliability requirements: as it observes in an opened section of the airplane fuselage, it must operate at temperatures down to -60°C and a pressure of 120 mbar.

Main contractor for the telescope procurement is a German consortium headed by the companies MAN Technologie and Kayser-Threde. CSEM has been contracted by MAN for the development and manufacturing of the secondary mirror assembly (SMA), which is due for delivery in the year 2000. The scope of the project delegated to CSEM comprises all actuation mechanisms, sensors, acquisition and drive electronics as well as imbedded software. Science flights of the SOFIA telescope will begin in 2001.

The SOFIA secondary mirror has a diameter of 350 mm and is actively driven along five degrees of freedom in order to be able to center and focus the telescope light beam. The major driver for the mechanism is the capability to "chop" the secondary mirror, hence the field of view of the telescope, in form of a stable square wave with an amplitude up to 1.2° and a frequency up to 20 Hz. The pointing accuracy has to be better than 0.7 arcsec. This chopping mode is used in the infrared wavelengths where the object luminosity is only marginally greater than the sky background by alternatively observing the object and subtracting the background noise.

2. DESIGN CONCEPTS

The Secondary Mirror Mechanism (SMM) is formally subdivided into two subsystems named Tilt-Chopping Mechanism (TCM) in charge essentially of fast tip-tilt and chopping actuation, and the Focus-Center Mechanism (FCM) which is responsible in particular for focus and centering alignment and, more generally for all offsets of the mirror positions.

The TCM and the FCM are functionally distinct but closely integrated physically in order to meet the very stringent requirements regarding the overall volume envelope of the SMM.

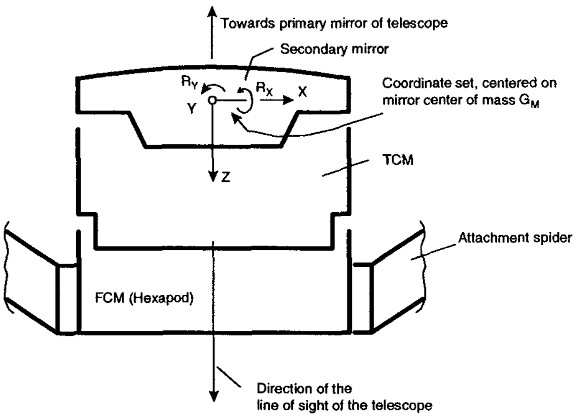


Figure 1 SMA Diagram

2.1. FOCUS-CENTER MECHANISM (FCM) CONCEPT

The SOFIA FCM consists essentially of an Stewart platform hexapod-like mechanism, capable of orienting is mobile base along all six degrees-of- freedom (DoF), although only five DoF's are actually operated. The main requirements are outlined in the table below.

Focus (z) range	± 5 mm
Focus increment	≤ 1 µm
Focus error	≤ 0.5 µm rms
Focusing speed	between 1 µm/s and 1 mm/s
Center (x,y) range	± 5 mm
Center increment	≤ 4 µm
Center error	≤ 2 µm rms
Centering speed	10 µm/s ... 1 mm/s
Tip-tilt range	± 0.312°
Tip-tilt increment	≤ 2 arcsec
Tip-tilt error	≤ 1 arcsec rms
Tip-tilt speed	between 2 arcsec/s and 0.5°/s

It must be noted that the use of the entire tip-tilt range (for instance for the chop offset) reduces the available focus and center range by about 0.65 mm

To gain space for the TCM, the hexapod is divided in two actuator groups, one with three vertical actuating legs, and one with three horizontal legs.

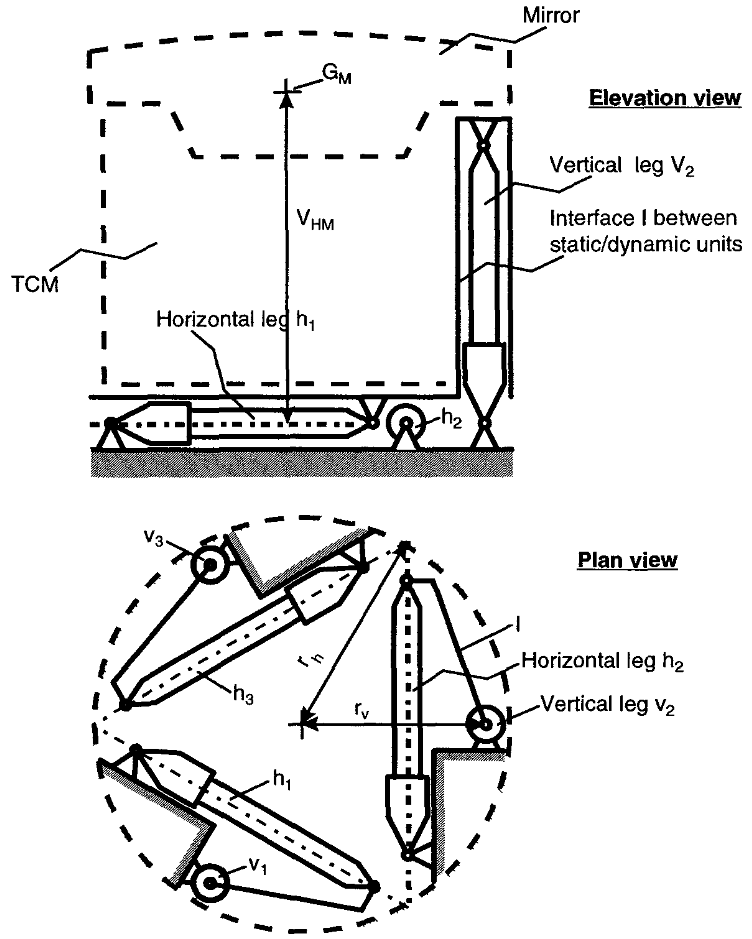


Figure 2 Principle of hexapod with three vertical and three horizontal legs

2.2. TILT-CHOPPING MECHANISM (TCM) CONCEPT

The TCM concept is illustrated in the figure 3 below. On a base constituted by the mobile (here upper) interface of the FCM, the TCM consists essentially of:

- A flexure pivot linked to the center of mass of the mirror holder. This pivot constrains the x,y,z directions as well as the torsion Rz, leaving essentially free both tip and tilt Rx and Ry rotations.
- Three actuator systems located in a 120 deg symmetry, each of which consists of a lever actuated by a linear motor which transmits the motion to the mirror and to a reaction compensation ring. Each lever has then three pivots, the central one is mounted on the base. The other two transmit an uncoupled vertical motion respectively to the mirror and to a reaction compensation ring. All links are constituted by elastic flexures.

- The reaction compensation ring moves in the opposite angular direction than the mirror, thereby compensating angular momentum.

The angular position of the mirror is detected by three non-contact displacement transducers located in correspondence with the mirror attachments, while the three axial forces to the mirror are monitored by load cells. The three radial attachments will receive only axial forces with average equal to zero, thereby effectively controlling only tip-tilt.

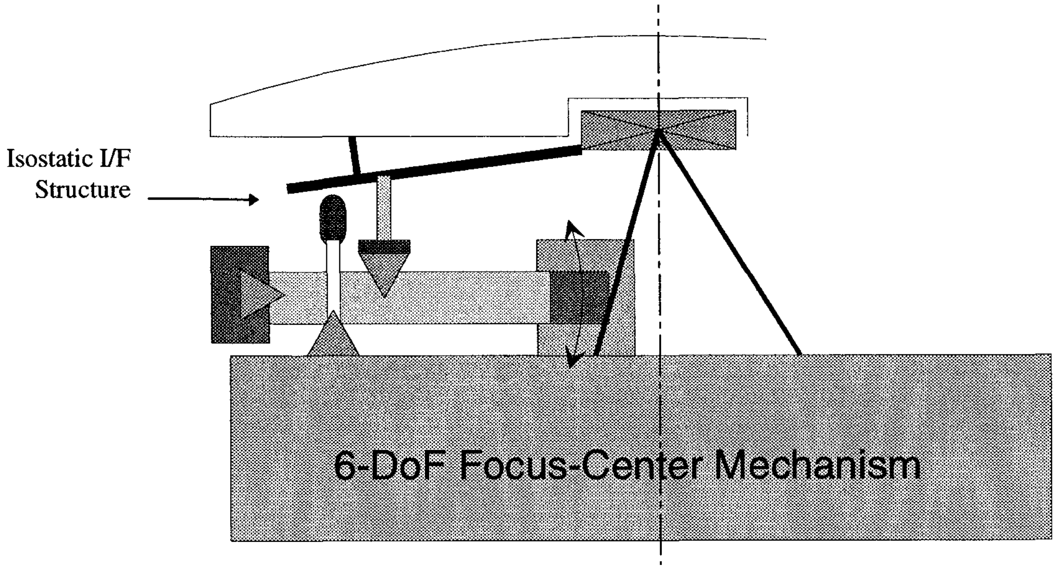


Figure 3 Schematic diagram of the TCM

Overall tilt and chopping range		0.625°centered about Z-axis
Tilt and chop angle		Chopping along any axis in the XY plane with 0.2° resolution and ± 0.5° stability during at least 1 hour
Amplitude peak-to-peak	range	0.002° to 0.625°
	maximum chop throw	± 0.312° from center/offset point
	set point accuracy	10% of commanded amplitude
	• end-point stability (rms) over 1 hour • accuracy of stop point • repeatability of consecutive periods	Maximum of: • 1% of amplitude • 0.0002°
Offset from Z-axis	range	± 0.25°
Settling time		≤ 5 ms for amplitude ≤ 0.06° ≤ 7 ms for amplitude ≤ 0.24° ≤ 10 ms for amplitude ≤ 0.6°
Square wave frequency	range	1 Hz to 20 Hz
	set increment	1 Hz
	phase adjustment	± 180° in 1° increments

Table 1 Chopping requirements summary

2.3. DESIGN HIGHLIGHTS

The design is characterized by a number of challenging and innovative aspects:

- Extreme compactness of the mechanism. The SMA allowed height is 300 mm, for an external diameter of 350 mm. This is far more compact than any modern secondary positioning/chopping mechanism either existing (Keck) or in project (ESO-VLT, GEMINI). The compact configuration is achieved by a very tight geometrical integration of the FCM and TCM stages.

- Novel hexapod mechanism for the FCM, with an original geometry and the use of flexures instead of conventional bearings.

- The compensation of angular momentum is obtained by a direct mechanical link between the mirror and a compensation ring which avoids a duplication of actuation and sensor systems. This is a major difference from previous concepts where the compensation mass is driven and controlled separately. The CSEM solution obtains thus various advantages for the mechanical layout and the control system.

- An extended dynamic closed loop bandwidth up to 140 Hz is achieved by means of a state space controller with Bessel filter characteristics.

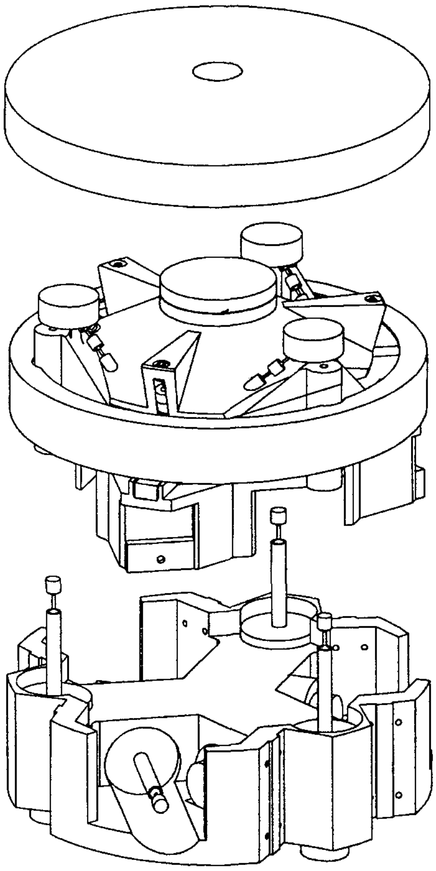


Figure 4 A partly exploded view of the SOFIA secondary mirror assembly, showing from top to bottom respectively the secondary mirror, the chopping mechanism (TCM) and the focus-center mechanism (FCM).

3. CHOPPING CONTROLLER

The following block diagram shows the overall configuration of the TCM control circuits.

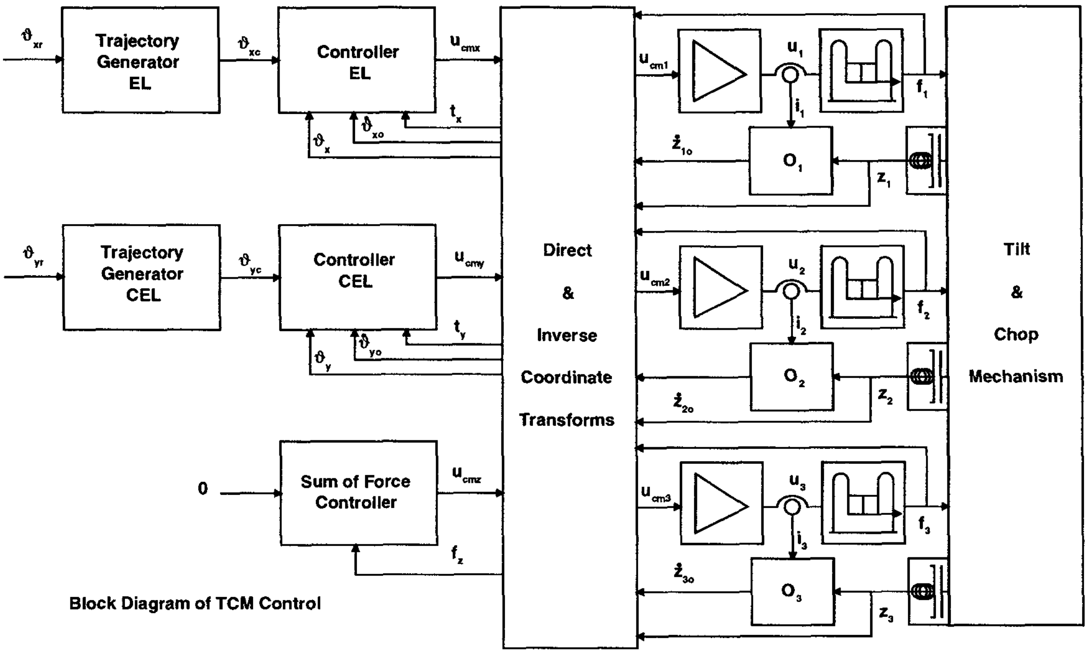


Figure 5 TCM control block diagram

Three uncoupled SISO controllers are foreseen which operate in mirror coordinates. There is one controller for the elevation axis R_x, one for the cross elevation axis R_y, and a sum-of-force controller which reduces any vertical force acting on the virtual mirror pivot, i.e. on the mirror suspension and guiding mechanism.

The elevation and cross elevation axis controllers receive position setpoints. These are either directly the position setpoints corresponding to the ideal rectangular reference profile as generated in function of user set amplitude and orientation, or trajectory setpoints which are derived from the ideal rectangular reference profile by prefiltering. The use or not of a trajectory prefilter is still subject to a trade-off of dynamic performance achievable versus excitation of structure resonance modes.

The elevation and cross elevation axis controllers are state space controllers, which process torque, velocity and position feedback. The sum-of-force controller is also a state space controller, but with sum-of-force feedback only. All three controllers generate command voltages. These command voltages are not input to virtual mirror axis power amplifiers and actuators, but they are transformed to coordinates so as to determine the command voltages of the three real power amplifiers. These power amplifiers apply in turn input voltages to the three actuators driving the TCM.

The actuator currents are measured by shunt resistors. Also, the three forces transmitted through the mirror insertion points are measured using load cells. This is useful for two reasons. First, a direct measurement of the forces transmitted to the mirror allows to better protect the virtual mirror pivot from vertical loads. Second, linear actuator thrust constants can vary from one actuator to another due to differences in permanent magnet magnetization. A comparison of force and current measurements allows to identify precisely the thrust constant of each drive axis of the TCM.

Three proximity sensors are used to measure the position of the mirror. The actual measured positions are very close to those of the mirror actuation points, which means that each sensor position corresponds to a single actuator displacement. No velocity sensors are used. In order to determine the velocity a reduced order state observer will be implemented.

The design of the controller is first performed by considering only the fundamental tilt flexures of the TCM. The controllers is then validated and improved by means of a simplified finite element model of the three-lever TCM system, in which the elastic properties of all members are represented.

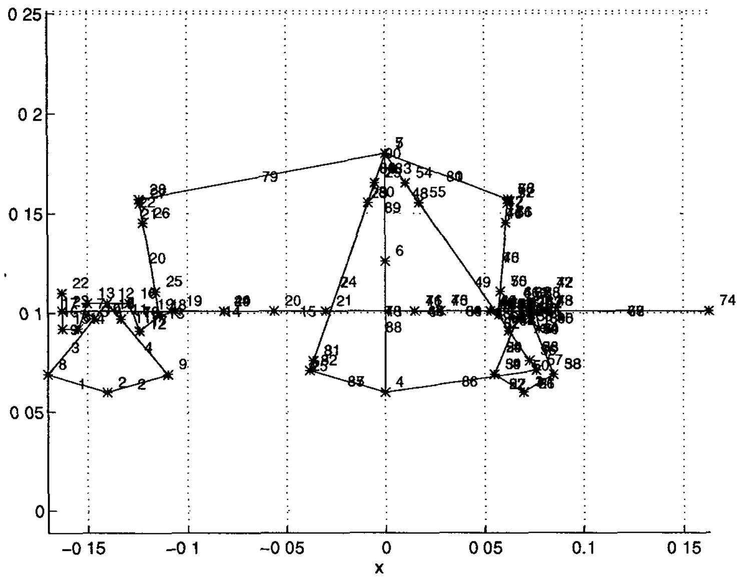


Figure 6 TCM preliminary FEM model

The dynamic behaviour of the model is expressed as

$$M\ddot{X} + D\dot{X} + KX = F(t)$$

where the matrices $M,\ D,\ K \in R_{492\times492}$, $F(t) \in R_{492\times1}$ describing a force vector in which all the elements are zero but three, $X \in R_{492\times1}$ being a state vector.

The modal analysis with the model, based on the latest design provides the results found in the next table. Note that many modes are found twice, once for each in-plane (XY) direction.

Frequency (Hz)	Predominant mode shape
29	Fundamental tilt mode
29	Fundamental tilt mode (orthogonal)
350	Mirror vertical displacement
390	Lever torsion about pivot
390	Lever torsion about pivot (orthogonal)
402	Mirror torsion

Through an order reduction, a simple model can be extracted from the above one. This model only involves twelve system modes that correspond to twelve lowest characteristic frequencies of the original model,

$$M_R \ddot{X}_R + D_R \dot{X}_R + K_R X_R = F_R \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix}$$

where

X_R is a state vector,

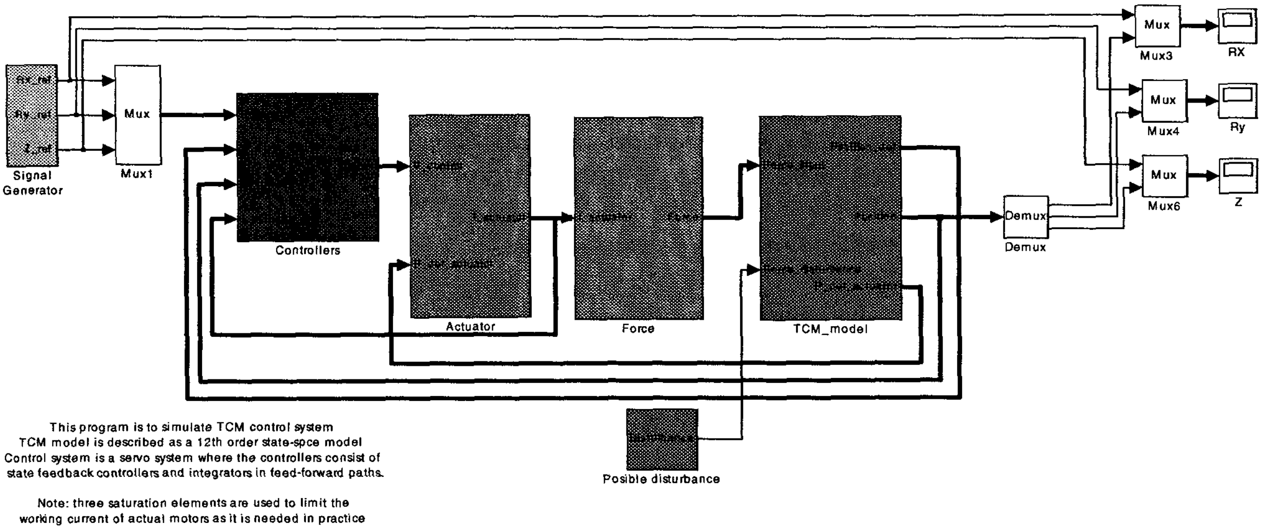
M_R, D_R, $K_R \in R_{12\times12}$ are coefficient matrices,

$F_R \in R_{12\times3}$ is a coefficient matrix for three force outputs of actuators.

Knowing the state vector X_R , the rotations R_X and R_Y with respect to X- and Y-axis and the linear displacement along Z-direction can be calculated by

$$R_X = C_X X_R,$$
$$R_Y = C_Y X_R$$
$$Z = C_Z X_R$$

where C_X, C_Y and C_Z are coefficient vectors.



This program is to simulate TCM control system
TCM model is described as a 12th order state-spce model
Control system is a servo system where the controllers consist of state feedback controllers and integrators in feed-forward paths.

Note: three saturation elements are used to limit the working current of actual motors as it is needed in practice

Figure 7 Matlab/Simulink® model

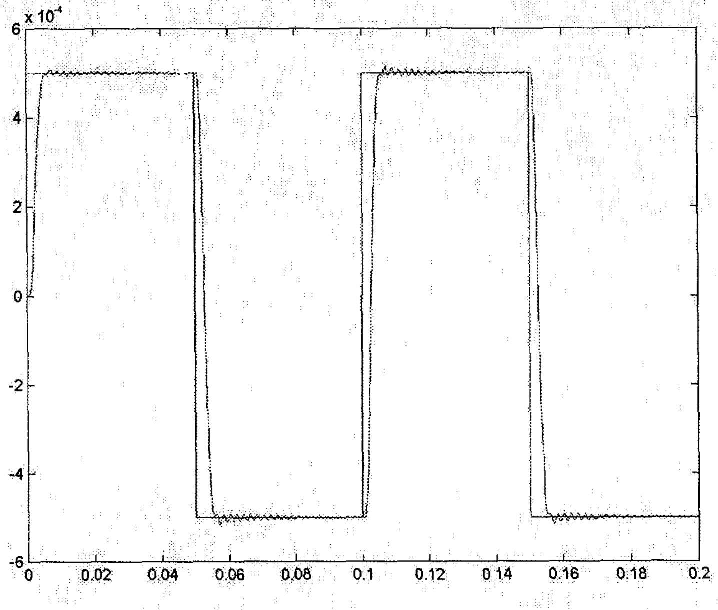


Figure 8 Chopping simulation

4. ACKNOWLEDGMENTS

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5. REFERENCES

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