Highly Dynamic and High Precision Self Balanced Optical Mechanism

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Abstract:
Ongoing developments of instruments reveal the need for fast and precise mechanisms [1]. These requirements are all the more significant when large payloads of hundreds grams, such as mirrors, optical plates, corner cubes or antennas are involved in the motion. Indeed, highly dynamic kinematics coupled with large inertia lead to parasitic reaction forces that interfere on the accurate measurement.
This paper describes the study of a tilt mechanism reaching 300µrad of stroke in less than 3ms while cancelling at the same time the reaction forces resulting from this fast motion:
Firstly a trade-off study leads to qualitative evaluation of the mechanism. Then a detailed mechanical design is performed to provide relevant model for automatic and control. Finally a test campaign is realized to characterize the prototype

Keywords: Piezo actuators, tilt mechanism, optical mechanism, self balanced system.

Background
The novelty of the mechanism relies on its ability to cancel reaction forces, while increasing the speed and the accuracy of the motion at the same time. This principle is patent pending by CNES. It implies the use of a dummy inertia that replicate the movement of the payload in a symmetrical manner. Actuators are used in free-free condition between the payload and the stabilising inertia. A dedicated guidance is used to maintain the optical element in suspension, authorising one degree of freedom.

Piezoelectric actuators are ideal when fast actuations of large payloads are specified on sub-millimetre strokes. Amplified Piezoelectric Actuators (APA®) [2, 3] are solid-state linear actuators offering large deformations (from 1 to 10% depending on the type). They are designed with an efficient mechanical amplifier and a pre-stress applied to the piezo ceramics. This design choice was initially performed to meet space requirements in order to offer a good ability to withstand external vibrations (due to launching). They passed many aerospace qualifications and they were selected in many EU and US space missions [4]. Elsewhere they can be easily integrated to get complete solid state mechanisms. This has been shown with a qualified XYZ stage for ROSETTA/MIDAS space instrument.

Specifications
The mechanism shall be a tilt devise. The total stroke should be 1 mRad. A step of 300µrad of stroke shall be reached in less than 5ms with a stability of +/-0.5µrad. The payload is a squared mirror. The total mass to be rotated, including the optical support, is about 1 kg and the moment of inertia 2500 kg.mm^2. Reaction forces shall be minimized in quasi-static and dynamic operations. The final prototype (***Figure 1***) shall be fully tested.

Figure 1, *Self balanced tilt mechanism prototype.*

Trade-off study
A trade-off study is considered at the beginning of the study in order to identify the best way to implement both actuators and payloads [7]. The chosen concept is the one that minimises the reaction force: its topology is chosen for the detailed design.

Description

The tilting motion is generated by actuators placed between the payload and the stabilizing inertia. These actuators are mounted in Free-Free condition in order to increase the speed of the motion and to balance the reaction forces resulting from inertial loads. The overall moving elements are suspended to the frame by a flexural guidance. Thanks to the use of compact Amplified Piezo Actuators (APA®), the payload and the reaction inertia can be self-crossed. Furthermore, the mechanism (***Figure 2***) is equipped with sensors in order to provide a smart motion when coupled with a real-time controller.

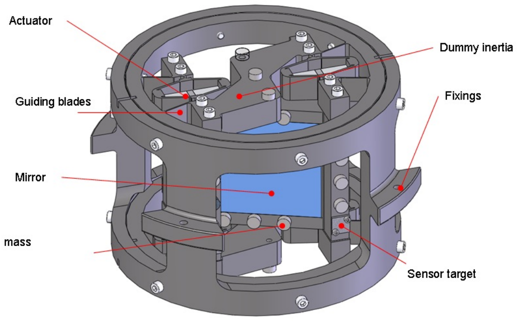

Figure 2, *CAD view of the tilt mechanism.*

Performances

The detailed design starts with the calculation of the reaction forces in static operation by Finite Element Method. Special care has been taken in the symmetrisation of the design, leading to static reaction force cancellation. In this regard the mechanism is axi-symmetrical and the fixing ears (***Figure 2***) are located in the middle plane of the frame. Therefore, unless each piezo actuator supplies 800 N of force to the payload, the static reaction force to the ground is estimated at 3mN. The modal analysis is then performed to obtain the vibration modes of the tilt mechanism. The first mode of vibration occurs at 244Hz. The actuation mode, symmetrical rotation of the payload and of the dummy mass, occurs at 1070Hz (***Figure 3***). This frequency value directly impacts on the speed of the motion. Elsewhere, the deformed shape of this mode also gives the modal displacement of both the optic and the stabilizing inertia.

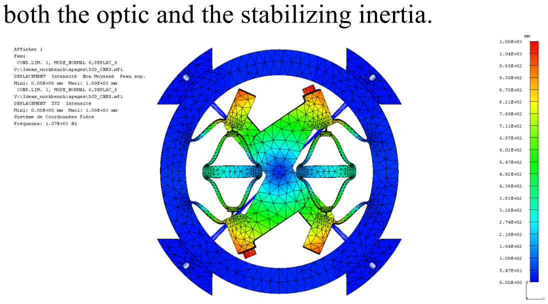

Figure 3, *Opposition-phase rotation deformed shape.*

This modal analysis is then used to draw the harmonic response of the mirror displacement when sweeping the input order at full excitation along a large bandwidth (1Hz – 4000Hz). The response (***Figure 4***) is similar to a second order low pass filter.

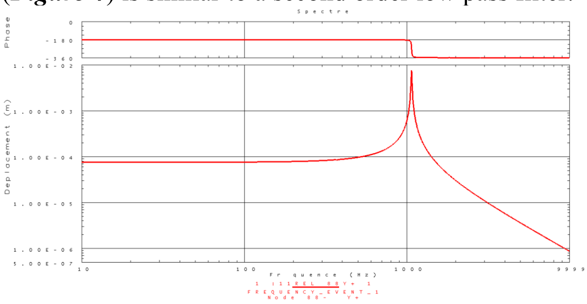

Figure 4, *Harmonic response to sine excitation.*

The bandwidth is drawn using a perfect mechanical balancing. It shows a clean modal background with no parasitic mode before and after the mechanical Eigen frequency. This ideal situation becomes downgraded when disequilibrium is created in the model. Indeed three kinds of imbalance may destabilize the dynamic model:

- Inertial imbalance between the payload and the dummy inertia (6% and 0.6%).
- Stiffness imbalance between the respective guidance (2.4% and 0.3%).
- Misalignment of both centres of gravity (0.1 mm).

A sensitivity study is then performed to analyze the influence of these sources of imbalance on the dynamic behaviour. The result is shown on ***Figure 5***. Actually the harmonic response (***Figure 4***) remains modified by the additional coupling of a parasitic mode at 374Hz.

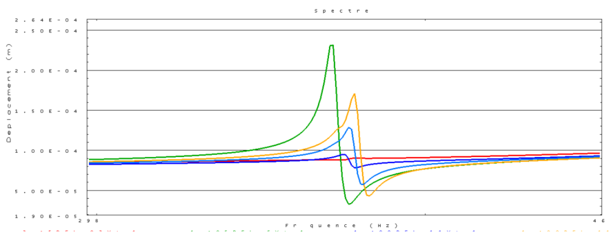

Figure 5, *coupling the parasitic mode with imbalance.*

The coupling of this parasitic mode is sensitive to inertia (green and dark blue curve) and stiffness (Orange and light blue curve) imbalances. The misalignment of the centres of gravity (red curve) shows no sensitive influence.

The 374Hz parasitic mode appears to be the in-phase rotation mode between the mirror and the dummy inertia.

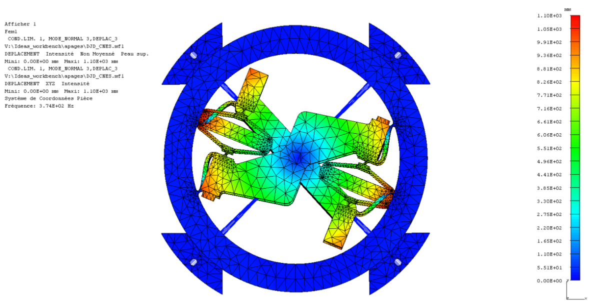

__Figure 6,__ In-phase rotation mode; deformed shape.

Drive and control

The four actuators of the mechanism respond to a single input order. Each actuator has its sensitivity calibrated in order to have similar displacement to single input orders. The hysteretic behaviour dispersion between actuators is assumed to be minimal when the piezo ceramics are selected from a similar batch of production. One single sensor and controller are used to control the motion in closed loop.

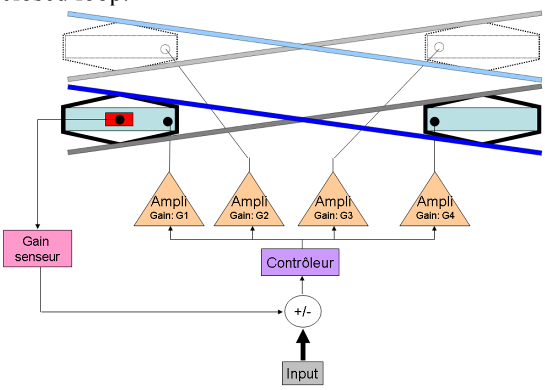

__Figure 7__, Drive and control strategy.

Thanks to the mechanical analysis, an electromechanical model is built to analyse the behaviour of the control loop by including the driver and sensor behaviours. This modelling phase allows the optimization of the regulator to achieve the best performances in closed loop when following a step-function command. The feedback control loop is based on a robust Proportional Integral Derivate regulator. A specific stabilizing filter is used to control the mechanical system (***Figure 8***). A stabilizing filter is placed behind the PID regulator to reduce phase shift and gain at high frequency.

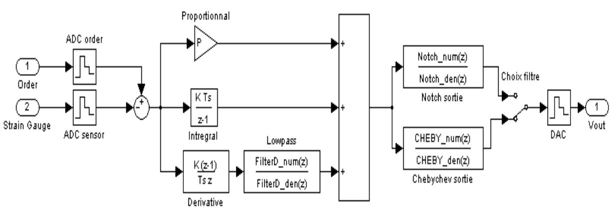

__Figure 8__, Control architecture.

In piezoelectric applications, it is recommended to use a sampling frequency at least 30 times the crossover frequency of the continuous design to preserve the behaviour of the continuous system at a reasonable degree. The sampling rate of the entire loop is chosen to be close to 20µs. The quantization of the analogue signal is 2^{-16} in order to be compatible with the high resolution of the mechanism. The modal analysis is done in open and closed loop to analyze the impact of the parasites modes. Indeed these modes can destabilize the loop. To reduce these impacts a solution is to place stop band filters on specific resonant modes to reduce their impacts in closed loop.

Both balanced and imbalanced model are analysed. A balanced model allows to reach 300µRad in 2.6ms while remaining stable at less than 0.5 µrad. In this condition the gain and phase margins are 20db and 79 degree respectively.

The use of pre-shaper input order allows a smooth acceleration that increases the gain and phase margin while decreasing the response time down to 2.8ms. An imbalanced model is computed (***Figure 9***).

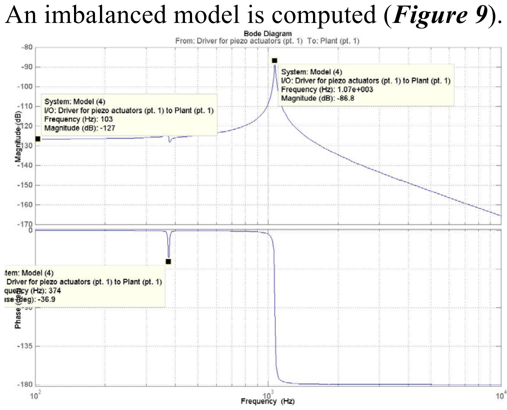

Figure 9, *System response including stiffness imbalance.*

As predicted, a parasitic mode appears at 374Hz in the bandwidth. Although this mode decreases the stability, the controller keeps enough margins to get a sufficient stability. Two possible performances can be achieved:

One the one hand, a response time of 3.7ms can be achieved with a stability of 0.5µRad. On the other hand a 5ms response time can be reached with a stability of 0.2µRad.

From the electric point of view, the mechanism is driven with a dedicated rack including: The driver provides +/-0.5Amps output current and 170V voltage to drive the four APAs® in parallel during the step response. A position sensor based on the strain gauges technology able to provide fine accuracy (+/-0.50% of the full scale) and a fine resolution. A controller built on the new real time UC75 including a real time target able to improve the performances of the control techniques of the actuators. This solution is chosen with regards to the high sampling rates needed to control the first modes of the tilt device. The UC75 includes a National Instrument Core based on Compact RIO@NI and the power of the Labview@NI Libraries to control any system with fast ticks with deterministic time up to 100kSample/s simultaneously on 4 channels.

The CompactRIO is powered by reconfigurable I/O (RIO) FPGA technology.

Mounting, calibration and testing

The mounting procedure is of interest since the integration bias shall be minimised. Thanks to its symmetrical configuration, the mechanical mechanism can be opened in a flexural manner to integrate the piezo ceramic. A dedicated mounting bench equipped with hydraulic jack is built to apply the opening force on the tilt device. A 1000N force is necessary to get a 15MPa preload on each piezo ceramic. When achieving the jack force, the mechanism self closes in a symmetrical manner. This procedure, similar to scissor opening, allows to get a self-aligned mechanism with preloaded actuators. The balancing procedure is performed in three steps. First of all, the mechanism is placed into a dedicated test bench in order to characterize the six degrees of freedom of both the mirror and the stabilizing inertia. The parasitic rotations are measured by the bench equipped with eddy current sensors ECS-PCB. These ECS-PCB are new proximity sensors developed by Cedrat Technologies for positioning applications up to 3mm [6]. The calibration of each actuator is performed in adjusting the gain of their respective drive amplifier (***Figure** 7*). The result is an equal displacement of each actuator, leading to symmetrical motions between the optical element and the dummy inertia. During this step of calibration the proximity sensors need to be decoupled from the mechanism to avoid parasitic reaction forces. The measurement is realized by suspending the sensors in a “sky hook” configuration by means of elastomeric elements.

Given a step signal input, 300µRad of rotation is achieved in less than 5ms with a stability of 0.5µrad.

The tilt mechanism is then placed onto a dedicated test bench for reaction forces evaluation.

A sine excitation (330µrad at 240Hz) is realised by the mechanism. The reaction torque is measured at less than 2.5mNm is this condition. This value is compared with theoretical value achieved without balancing inertia: 1.9N.m. The benefit of self balanced mechanism in sine excitation is then evaluated at 1/800 reaction force reduction.

The following ***Figure 11*** sum up the performances achieved with the tilt mechanism:

The second step of the balancing procedure aims at placing the centre of gravity of both the payload and the dummy inertia into the centre of rotation. This procedure requires a micro vibration table which characterizes the reaction forces. The balancing is achieved by the addition of masses. Finally both the optic and the stabilizing inertia are balanced in dynamic operation. Masses are added in order to compensate stiffness and / or inertia disequilibrium.

At this stage of the project the dynamic mechanical behaviour is characterised through the admittance curve. Since the electrical resonance frequency (in voltage) is similar to the mechanical resonance frequency, it is possible to get the dynamic behaviour of the tilt mechanism from the admittance curve. The result is a single coupled mode at 1 kHz. Actuators ability to get the actuation mode is very high (33% of electromechanical coupling coefficient). Elsewhere no parasitic mode occurs between (1Hz-4000Hz). This situation is ideal for drive and control since a fast regulator can be implemented into the controller without risking any instability of the loop.

Results

The following ***Figure 10*** shows the response time achieved with the tilt mechanism:

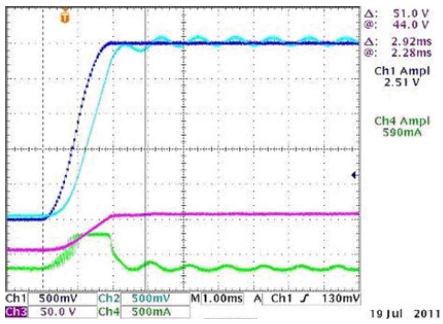

Figure 10: *Step response: displacement (light blue), order (blue), voltage (pink) & current (green)*

SPECIFICATIONS			RESULTS
PAYLOAD:			
Inertia	Kg.mm^2	2500	2500
Mass	Kg	1	1
STROKE:			
Total	mRad	1	1.385
Steps	µRad	300	300
RESPONSE TIME	ms	<5	4.3
STABILITY	µRad	<0.5	0.5
ACCURACY	µRad	<10	2
RESOLUTION	µRad	<0.1	0.138
REACTION FORCES / TORQUES	N/N.m	TO BE MINIMIZED	2.5 mNm @ 240Hz (1/800 reduction ratio)
			[0.1 N ; 6 mN.m] over 300Hz Bandwidth

Figure 11: *Mechanism performances*

Acknowledgment

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Conclusions

The original CNES idea of self balanced optical mechanism [5] can be carried out thanks to the use of Cedrat Technologies Amplified Piezo Actuator. Fast and precise motion of optical elements can be achieved while minimising the reaction dynamic forces.
This principle can be applied to several optical applications: tilt of an interferometer's optical blade, rotation of a mirror for optical beam deviation, antenna pointing or trimming. In addition fast linear motion such as focusing lens can be addressed.

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