Drag-free control design for the LISA space mission

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Abstract

In this thesis, the drag-free control design for the space mission Laser Interferometer Space Antenna (LISA) of the European Space Agency (ESA) is addressed. LISA will be a space-based gravitational wave observatory, which launch is scheduled for 2034. The gravitational waves are undulatory perturbations of the space-time grid that are generated by some astrophysical phenomena (i.e., merging black holes). They can be detected by measuring the relative distance variations, by means of a laser interferometer, between two free falling bodies (called test-masses) located at far distance. The current LISA concept consists of a constellation of three spacecraft travelling on different inclined heliocentric orbits, resulting in a Sun-facing spinning triangle with an average side length of $2.5 \cdot 10^9$ m. Each spacecraft carries two moving optical assemblies, each of which is composed by a telescope, an optical bench for the laser interferometry and an electrostatic suspension system. Two suspended cubic test-masses, used to perform the scientific experiment, are located inside the electrostatic suspensions. Therefore, a single LISA spacecraft is a multi-body system characterized by 20 degrees of freedom (DoF).

In view of the mission preparation, ESA started several feasibility studies and, in particular, one regarding the DFACS (Drag Free and Attitude Control System) to understand if the current spacecraft concept can be compliant with the expected functional and performance requirements. The DFACS clearly plays a key role in the mission, since it makes the test-masses move in free falling conditions, thus allowing detection/measurement of gravitational waves. However, its design is challenging, due to the complexity of the system, the relatively high sensing and actuation noises and the strict performance requirements that have been established by ESA. To the best of the Author's knowledge, no exhaustive solutions to the LISA DFACS problem are available in the literature. Therefore, the main goal of this thesis was to develop a DFACS for the LISA mission, able to meet the mission performance requirements and eventually the best performance achievable. To meet this goal, the following activities were carried out: i) literature review to find useful information for the control system design to be integrated with the design inputs ii) development of nonlinear, linearized and decoupled models for the spacecraft multibody dynamics, iii) design of a robust high-performance controller for the science phase, iv) realization of a simulation

environment, v) assessment of the requirements, parametric and disturbance ranges that affect the control performance, vi) identify potential flaws to be investigated or improved in future studies.

In the present thesis, some basic concepts about the gravitational wave observatories are initially recalled. Then, the LISA system is described by merging the LISA literature with the ESA design inputs to have useful information to be used for the control design (i.e., plant, actuators, sensors, and disturbance characteristics). After the introduction, a nonlinear model of the LISA spacecraft dynamics is derived and validated in simulation. It may be noted that deriving such a model is in general a difficult task since, as mentioned above, a LISA spacecraft is a multibody system with 20 coupled degrees of freedom. To the best of the Author's knowledge, the model proposed in this thesis is the first analytical nonlinear model of the LISA spacecraft available in the literature. It describes the relevant dynamics and it is a fundamental tool for control design (via linearization), analysis and simulation. Afterwards, linearization around the drag-free working point and the decoupling analysis are performed. The LISA plant has 18 inputs, 17 outputs and is unstable. According to the decoupling analysis, it can be fully decoupled. However, standard decoupling approaches, like those based on a pseudoinverse of the lower half of the B matrix of the state space model, do not consider actuation constraints (i.e., acting on certain states only with specific actuators as required by some LISA functional requirements). To overcome this issue, a novel decoupling method able to deal with the actuation constraints is presented. This method consists in performing a constrained inversion of the lower half of the B matrix of the state space model, by solving an optimization problem. Constraints on the coefficients of the decoupling matrix are set, while the inversion error with respect to the nominal pseudoinverse is minimized in the objective function. However, even though the constrained inversion provides a decoupling able to deal with the actuation constraints, it introduces an inversion error and consequently it leaves some residual couplings that could affect the stability of the closed loop control system. The problem is investigated theoretically and a sufficient condition for the asymptotic stability of the closed loop system is found. The proposed method is general and can provide a decoupling matrix that satisfies the actuation constraints and minimizes the residual couplings, thus allowing the possibility to have a decoupled control architecture with a parallel of SISO controllers and to use only specific actuators to control certain states.

After the modelling activities, DFACS control design is carried out. When the system enters the Drag-Free mode, the task is to control all the 20 degrees of freedom simultaneously. In this phase, it is mandatory to compensate for all the possible disturbances and guarantee the free fall condition of the two test-masses on board. All the spectral densities of the output signals are subject to strict performance requirements at nanoscopic and microscopic scale. As remarked above, control of such a system is a challenging problem and no exhaustive solutions were available before the work presented in this thesis. At the time of the design activities, it was not even clear if the aforementioned requirements could be met. The decoupled model of the plant is exploited to have a control architecture that consists in a parallel of Single Input Single Output (SISO) controllers. Each one is designed with the mixed sensitivity H-infinity method, since it can systematically manage fundamental quantities for this kind of control problem, such as the noise and requirements shape functions in the frequency domain.

Another novel aspect of the developed DFACS regards an algorithm for the reference generator of the spacecraft attitude control loop. This algorithm computes the spacecraft attitude relative to the local constellation frame, starting from the azimuth-elevation angles relative to the incoming laser beams measured by the laser interferometer. This allows to control the spacecraft attitude avoiding the usage of noisy star trackers in science mode, to keep the x-axis of the spacecraft frame pointing towards the constellation center and the z-axis perpendicular to the constellation plane.

A theoretical analysis of the performance requirements is then carried out. It is proved that the bounds on the spectral densities of the test-mass translation coordinates cannot be satisfied in some small ranges at low frequency due to the high sensing noises. The theoretical noise shapes that allow to satisfy the performance requirement have been determined. Then, a μ-analysis and a worst-case gain analysis are carried out, showing satisfactory robustness properties against parametric uncertainties. Such robustness properties were also confirmed by extensive Monte Carlo simulations where the H-inf controllers have been tested on the nonlinear system in a Matlab-Simulink environment. In all the Monte Carlo simulations, the performance requirements on the spectral densities of the output signals have been fulfilled (except for the theoretically unfeasible ranges).

One last analysis carried out in this work regards the effects of micro-meteoroid impacts. They can be modeled as impulsive forces and torques acting on the spacecraft surface, which determine attitude perturbations. Impacts with different direction and intensity acting on different contact points have been simulated. In case the impact is not too strong, the spacecraft can still receive the laser beams arriving from the other spacecrafts and can reject the impulsive disturbance.

To conclude, the results showed that the control system and the current spacecraft design are potentially able to achieve the functional and performance requirements. It must be remarked that, during the present study, the LISA mission was under Phase A and therefore a preliminary spacecraft concept was considered. Once the entire spacecraft design will be consolidated a second issue/revision of the LISA control system design shall be performed. This work can be used as a baseline for future developments of the Guidance, Navigation and Control system for the LISA mission.