Contribution to the Dynamics of a Solar Sail in the Earth - Sun System

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Solar sails are a new concept of spacecraft propulsion that has more adepts everyday. The idea is to provide a spacecraft with a large membrane mirror such that the impact of the photons emitted by the Sun and their further reflection produce momentum on it. For the moment there has yet not been a successful deployment of a solar sail in space, although lately there have been a couple of attempts, Cosmos 1 and NanoSail. Both missions failed before the spacecraft could get to the nominal orbit, not being able to deploy the solar sail and test the technology. In the last years, space agencies have started to invest in this technology and it seems that at some point solar sails will become a reality. Studies on the use of a solar sails have been done in the past. One of the reference books in the field is [McI99] where most of the studies on the subject up to 1999 are summarised. The design of solar sails, the force models for the different structures, the dynamics on heliocentric or geocentric orbits are some of the subjects covered in this book. Nevertheless, dynamical system tools have had a small influence in this area. The use of dynamical systems tools in astrodynamics is not new for the UB-UPC Dynamical System group. Lots of studies have been made in the past applying this tools to several astrodynamical problems [GLMS01a, GLMS01b, GJMS01]. We propose to use similar ideas to navigate through the Earth - Sun system with a solar sail. One of the goals of this thesis is to study, in an extended way, the natural dynamics of a solar sail in the Earth -Sun system. This is a first step of a more ambitious project of designing strategies for different kind of mission application such as, station keeping strategies around equilibrium points, periodic orbits and invariant tori, or consider using invariant manifold to go from one region on the phase space to the other in a natural way. Either using solar sails or other type of low -thrust spacecraft propulsion, covering most of this aspects within the framework of dynamical systems. In Chapter 1 we review some of the known aspects on solar sails and explain the model and problems that we want to face. We use the Restricted Three Body Problem (RTBP) adding the solar radiation pressure on the solar sail as a model and study some of its most Introduction relevant dynamical properties. It is well known [Sze67], that the Restricted Three Body Problem in synodical coordinates has 5 equilibrium points, which correspond to the position where the gravitational attraction of the two primaries, Earth and Sun, compensate. When we consider the extra effect of the solar sail, there is a 2D family of new equilibria, parameterized by the sail orientation. These artificially generated equilibrium points open a wide new range of possible mission applications, the Geostorm mission and the Polar Observer are two examples [McI99]. The Geostorm is a mission concept where a modest sail is placed Sunwards of the classical Earth -Sun L1 point. Then using a magnetometer to detect the solar wind polarity enables to double the time of alert of a conventional L1 Halo orbiter such as SOHO. The Polar Observer aims to use an artificial equilibrium point displaced above the ecliptic plane, high above one of the Earths poles. This would provide constant real-time views of the polar latitudes for studding, for instance, climate change. Most of these equilibrium points are unstable, hence a station keeping strategy is required if we want to maintain the solar sail close to equilibria for a long time. In Chapter 2 we derive a station keeping strategy using dynamics system tools. The idea is to understand the variation of the phase space when the sail orientation is changed. We can see that the linear dynamics around these equilibrium points is closely approximated by a saddle × centre × centre motion. Hence when the sail is close to the equilibrium point its trajectory will escape along the unstable direction. If we change the sail orientation, the fixed position varies slightly, and so do the stable and unstable directions. We want to find a new sail orientation such that the unstable direction of the new equilibrium brings the trajectory back to a vicinity of the initial position. Furthermore, one must take into account the centre projection of the motion, as this one can result of an unbounded growth. We have applied these strategies for the two missions mentioned before maintaining the solar sail around the desired equilibrium point up to 30 years. We have also tested the robustness of our strategies including errors in the position and velocity determination, as well as errors on the orientation of the sail at each manoeuvre. We will discuss the effect of these errors on the controllability of the solar sail. Further on, we would like to extend these ideas to derive station keeping strategies around periodic orbits. For this reason we need to have a more complete understanding of the non-linear dynamics around an equilibrium point, and how it varies when the sail orientation changes. In this thesis we have focused on the motion in a close neighbourhood of the displaced L1 equilibrium point for a solar sail, called SL1. We have developed numerical tools for the study of the bounded motion close to SL1. These techniques are very general and can be applied around other equilibrium points. Due to the instability of the region, we cannot take arbitrary initial conditions and integrate them numerically, as they would quickly escape from the vicinity of the fixed point. For this reason, we propose to perform the reduction to the centre manifold around the different equilibrium points. We want to find a high order approximation of the motion on the centre manifold and use it to describe the motion on it. As the system is only Hamiltonian for a small set of values of the sail orientation we cannot take advantage of this as in [Jor99, JM99] where the motion around the collinear points of the RTBP is discussed. Instead, we compute the power expansion of the graph, $y = v(x)$, of the centre manifold around an equilibrium point up to high order [Sim90, Har08]. We are interested in an efficient algorithm as we want to do the reduction to the centre manifold for different sail orientations. In Chapter 3 we describe this algorithm and also give some details on the implementation of an efficient code. We also compare the efficiency of our algorithms with the Lie series method, for the particular case of a sail perpendicular to the Sun -line, when the system is Hamiltonian. Finally, in Chapter 4 we describe the dynamics around different equilibrium points close to SL1. We have computed the families of periodic orbits by means of a continuation method. We have also used the approximation to the centre manifold obtained in the previous chapter to have a description of the periodic and quasi-periodic motion in an extended neighbourhood of these equilibrium points. Around each of the equilibrium points we find families of planar and vertical periodic orbits related to the two frequencies defining the centre motion. Families of Halo -type orbits can also be found. The interaction between the two frequencies gives rise to families of invariant tori. At the end of this dissertation we summarize the main results and point out some possible directions for future work.