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The Interaction of Structural Dynamics with the Orbital Mechanics of Solar Power Satellites

Summary Report

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The Interaction of Structural Dynamics with the Orbital Mechanics of Solar Power Satellites

Summary Report

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1 Introduction

Space Based Solar Power concepts promise the generation of large amounts of renewable power by launching vast Solar Power Satellites (SPS) into space and beaming the power back to rectennas on Earth. Due to diffraction physics, large scale arrays delivering 2GW of power to the ground will be of the order of a kilometre in length and have masses of between 2,000 and 10,000 tonnes. There is significant and recently renewed interest in pursuing Space Based Solar Power (SBSP) technology, due to the need to decarbonise the energy supply to achieve Net Zero goals and a recent focus on achieving energy security. SBSP offers a number of potential advantages over the majority of terrestrial renewables, including high-capacity, dispatchable power that can be delivered across a large area.

Given the size of SPS there is a potential for their structural dynamics to couple with their orbit mechanics, leading to the need for orbit correction. In addition to the scale of such structures there is also considerable challenge to be met in maintaining their shape and integrity when in orbit due to the tendency of any large orbiting structure to undergo various statically and dynamically induced deformations. This study, therefore seeks to investigate the magnitude of the coupling between the orbital mechanics and the structural dynamics of Solar Power Satellites and the insight gained will lead to the development of design guidance for optimising SPS structures.

This study has been conducted by Frazer-Nash Consultancy Limited working collaboratively with the University of Strathclyde. The study has been conducted on behalf of the European Space Agency (ESA) through the Open Space Innovation Platform (OSIP).

1.1 Project Scope

The objectives of this study are to:

- Investigate the magnitude of coupling between the structural dynamics and orbital mechanics of Solar Power Satellites;
- Quantify the potential disturbance to the orbit of Solar Power Satellites;
- Devise novel outline design guidelines for the structure of Solar Power Satellites to minimise the disturbance to their orbits;
- Identify trends in the structural response for a range of design parameters.

The first part of this study has considered the use of established finite element methods to quantify the structural response of a typical sparse flexible structure in the frequency domain. This follows a well-recognised analytical approach to determine the mode shapes and modal frequencies for an SPS structure. The key challenge being the analysis of such a vast spacecraft which lacks a traditional support frame/structure.

The second part of this activity has made use of a numerical perturbation analysis to investigate the effect of the SPS structural dynamics on the orbital mechanics. This has been coupled with a ray tracing study, to assess the effectiveness of the deformed SPS structure.

The combination of these analytical methods has been instrumental in enhancing our understanding of the potential coupling between the structural response and orbital mechanics, and the impact this has on the design of such a SPS.

1.2 Project Structure

The project is structured as a number of discrete Work Packages (WPS), as follows:

- **Work Package 1: Structural Modelling** – Characterise the structure of the SPS and development of a Finite Element (FE) representation of the CASSIOPeiA SPS, which forms the basis of the study.
- **Work Package 2: Dynamic Structural Response** – Analysis of the FE model in the frequency domain to determine the fundamental low frequency modes of the SPS.
- **Work Package 3: Orbital Mechanics** – A review of the orbital mechanics for the SPS, focused on the excitation of modes and the interaction of the modes with the SPS orbital position and control.
- **Work Package 4: Design Requirements** – Draw together the over-arching conclusions from the study and outline a set of design requirements.

These linked work packages have been managed in a project workflow, as shown in Figure 1.1. This workflow progresses from the characterisation of the SPS structure and an understanding of the orbital loads to the development of two analytical tools. The benefit of these two toolsets is that they can be used to assess the response of the SPS, ranging from the vibration modes of the SPS, to the dynamic response of a structure that exhibits interactions between the structural dynamics and orbital mechanics. Together these analytical tools have been used to investigate the interaction between the orbital mechanics and structural dynamics of a SPS and derive a set of outline design requirements.

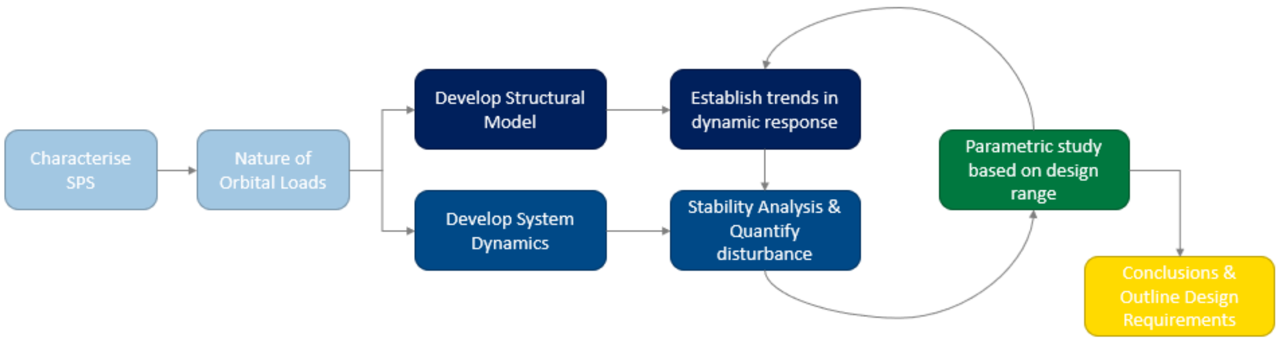

Figure 1.1: Project workflow.

2 Characterisation of the Solar Power Satellite

The CASSIOPeiA SPS consists of a helical structure with high concentration solar Photovoltaic (PV) panels orientated to face solar North and South. These panels collect light reflected by large reflectors positioned at either end of the structure. The design uses an integrated sandwich panel which incorporates the photovoltaic and microwave elements forming an orientable phased array into a single element. This phased array allows the microwave beam to be steered through $360°$ resulting in a design where the mirrors can be orientated to face the Sun at all times and allow the beam to rotate to target rectennas on the ground. A key feature of the CASSIOPeiA design is that it seeks to utilise as much solid-state functionality as possible to eliminate moving parts and increase reliability.

For the purpose of this study, the 2GW "2 Sun" CASSIOPeiA concept operating in geostationary orbit (GEO) has formed the basis of the analysis and calculations.

Much of the CASSIOPeiA research to date has focussed on the overall geometry, the distribution of PV panels, antennae and reflectors, the infrastructure required on the Earth, and estimates of yield. There is very little information available that describes the supporting structures and, as such, no detailed drawings or CAD upon which to base an FE model.

Figure 2.1 provides an overview of the assumed SPS structure, including the density (ρ), Young's Modulus (E) and Poisson's (ν) of the modelled components. Text on this figure has been colour coded to highlight whether data has been assumed, supplied, or has been calculated from supplied/assumed values.

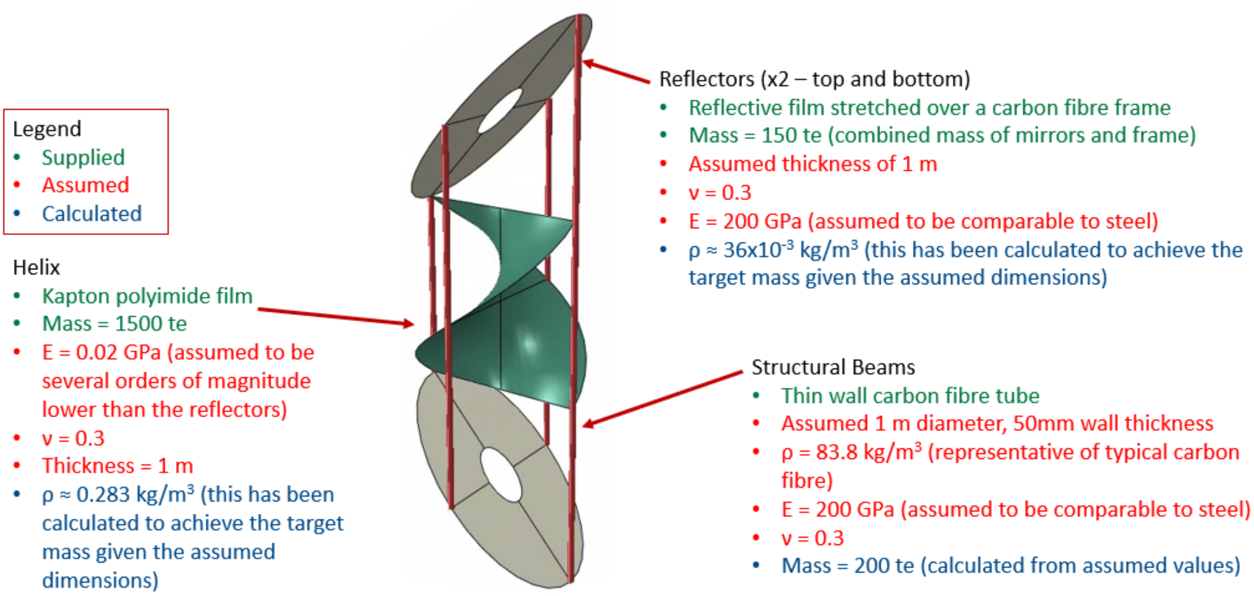

Figure 2.1: Overview of CASSIOPeiA Concept

3 Orbital Loads

The review of the orbital loads and of the attitude stability of the SPS has shown that the following loads may cause deformation of the SPS structure:

- Gravity gradient
- Microwave beam force
- Attitude control thruster force
- Solar Radiation Pressure (SRP)

Assuming the SPS keeps pointing towards the Sun, the first three loads depend on the position vector of the SPS relative to the Earth. The SRP is a constant load, i.e. it does not vary along the orbit, given that the attitude of the SPS is constant towards the Sun. Its result is a constant force and a constant deformation, which could be designed for. The other three load types are ones that can cause deformation varying during the orbit. This deformation can in turn change the resultant of the SRP force, leading to an effect on the orbital dynamics.

4 Conclusions

A study has been carried out to investigate the magnitude of the coupling between the structural dynamics and orbital mechanics of Solar Power Satellites.

The potential interaction between the structural dynamics and the orbital mechanics for such a sparse flexible structure has been achieved through the development of a finite element model alongside a numerical analysis approach. The combination of these analytical methods has been instrumental in: quantifying the potential disturbance to the orbit of an SPS, identifying trends in the structural response for design parameters, and in devising a set of outline design guidelines.

A leading SPS design, CASSIOPeiA, has been characterised to enable an analytical model to be developed for the purpose of this study. This characterisation has shown that, alongwith many of the leading SPS designs, CASSIOPeiA currently lacks key design details such as material selection and the degree of structural support. This study has focused on CASSIOPeiA operating in GEO and therefore, it should be noted that the conclusions are specific to GEO and would likely differ for a Medium Earth Orbit (MEO) and a Low Earth Orbit (LEO).

A review of orbital loads has been conducted as part of this study, considering both loads that are constant and loads that vary with orbital position. The gravity gradient acceleration has a period of half a day, and therefore presents the lowest excitation frequency of 2.3×10^{-5} Hz. For the baseline CASSIOPeiA configuration, the response frequency of the first flexural mode is two orders of magnitude greater than the excitation frequency.

Solar radiation pressure, which for CASSIOPeiA is a load that does not vary with orbital position, results in negligible displacement between the two reflectors. In response to the loads that do vary with orbital position, the maximum displacement of the reflectors is 2.88 m; this equates to 0.14% of the SPS diameter and is therefore tolerable. Therefore, the deformation of the baseline CASSIOPeiA design that varies along the SPS orbit is not expected to cause an interaction between the structural and orbital dynamics and will have negligible effect on the SPS performance.

A parametric study has been undertaken with the objective of investigating trends in the dynamic response of the CASSIOPeiA structure for a range of design parameters. The SPS mass and SPS length were identified as the most influential parameters on reducing the modal frequencies, thus potentially bringing them inline with the excitation frequency. Adjusting the mass distribution for the CASSIOPeiA model does not have a significant impact on the response frequency, and order of magnitude changes to the stiffness of the helix, reflectors and structural beams in isolation does not have a significant impact on reducing the response frequency.

As part of the parametric study, a combination of increasing the mass and the length of the SPS model was investigated. For a 12km length model, representative of longer SPS design such as MR-SPS and SPS-Alpha, an increased total mass of 300,000 tonnes resulted in a response frequency of 4.28×10^{-5} Hz. This response frequency is much more closely aligned to the excitation frequency of the gravity gradient acceleration. For this significantly increased mass (300,000 tonnes) and length (12km) the maximum deformation is approximately 120 metres (i.e. 6% of the SPS diameter). The closer the alignment between the excitation and response frequencies, the larger the amplitude of the orbital varying displacements (i.e. the amplitude of structural vibrations).

Most notably, the effect on the orbital dynamics is small, with variations of the order of 10m in the semi-major axis and 10^{-3} degrees for the argument of pericentre. However the deformation does result in a reduction in the SPS efficiency, measured as the fraction of sunlight that is captured by the helix.

The following design guidance may be drawn:

- The structure of the SPS will need to be assessed and designed to accommodate all construction and operating loads, including constant and orbital varying loads.
- As a matter of good engineering practice, the modal frequencies of the SPS should be determined at all stages of the structural design process and compared with first and second order orbital frequencies.
- For extremes of SPS design, deformations due to orbital varying loads may become significant (relative to the SPS size) and should be assessed statically or dynamically.
- For the range of design parameters (mass and length) exhibited by the current leading SPS concepts, interaction between orbital mechanics and structural dynamics is not expected to be an issue.
- Structural vibration may become an issue for SPS performance due to potential misalignment. However, this can easily be assessed using commonly used Finite Element software. For the example of the 12km long SPS, the total SPS mass should not exceed 100,000 tonnes in order to achieve a sunlight capture efficiency of 90%.
- Structural vibration may become an issue for the structural integrity of an SPS. However, this can easily be assessed using commonly used Finite Element software. Structural integrity and misalignment can be assessed simultaneously.
- Formal assessment of satellite vibration on orbital dynamics should be undertaken at key design gates as an ongoing check. It is likely that there will be sufficient stiffness in the design, to mitigate concerns of alignment and structural integrity, thereby ensuring that deformations are relatively small in comparison to the overall size of the satellite.

5 Recommendations

Based on the conclusions of this study, the following recommendations are made for future work to further develop SBSP technology:

- **Investigate the fatigue performance of SPS designs:** It has been identified that structural vibration may become an issue for the structural integrity of large mass SPSs. A study is recommended to quantify component stresses and assess the fatigue performance over the operating life of an SPS. This may be extended to consider the fatigue performance of composites, which are likely to be used in many SPS designs.
- **Orbital Mechanics for a range of SPS concepts:** A study to research and quantify the range of orbital loads on SPS spacecraft in general, and the implications on their stability.
- **Attitude and Orbital Control Systems (AOCS) for other SPS designs:** AOCS considerations are particularly concept specific and the thruster forces that have been considered in this study are specific to CASSIOPeiA. It is recommended that a study is undertaken to consider the variation in the AOCS requirements and potential design solutions for other SPS designs.
- **SPS design development:** From the review of various SPS concepts, it has been identified that most leading concepts currently lack significant design detail. It is recommended that a study is carried out to build on the outputs from this work, focused on how the guidelines are used to develop the more detailed design for the SPS class concepts.
- **Development of an Orbital Dynamics Toolset:** A study to formulate an Orbital Dynamics toolset, which can be used throughout the SPS design process to streamline the perturbation analysis.

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