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Effect of (visco-)elastic deformation on the longitudinal libration of Europa's shell

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Abstract

The libration of Europa's shell in the presence of a subsurface ocean has been previously studied by considering that Europa's internal layers behave rigidly. However, at tidal frequency, Europa's interior is not rigid but experiences deformations as a response to the acting diurnal tides and the librations themselves. In this study, we consider the effect of deformation on the libration dynamics of Europa's shell by assuming that Europa's response at the frequency of the forcing can be considered as being nearly elastic. We show that nearly elastic deformation (of mainly the shell) substantially reduces the amplitude of the shell's librations to values only slightly larger than the ones corresponding to the libration of the rocky mantle.

1. Introduction

Due to the presence of a subsurface ocean, Europa's icy shell and deep interior may perform differential longitudinal librations as a response to Jupiter's gravitational torque. Although the putative ocean acts as a decoupling layer from a mechanical viewpoint, the rotational motion of the icy shell remains coupled to the motion of the deep interior by gravitational and pressure coupling torques. The influence of these internal coupling torques on the rotation of the shell has been extensively studied for the case in which the shell behaves as a rigid body [1, 6, 9]. However, at the frequency of the acting forcing (equal to the orbit's mean motion), the response of the shell to the acting diurnal tide and to the librations themselves is most likely to be viscoelastic, or at least nearly elastic [2]. Hence, in this study we include the effect of deformation into the description of the libration dynamics of a layered Europa with a subsurface ocean in order to analyze whether (visco-)elastic deformation has an important impact on the forced longitudinal librations experienced by the shell.

2. Rotational Dynamics

In our modeling, we assume that rotational variations and inertia increments due to mass displacements are small. These assumptions allow us to describe the experienced rotational variations by the so-called linearized Liouville equations [7, 8], in which the axial component - which describes longitudinal librations - is decoupled from the $x-$ and $y-$components. Moreover, from the viewpoint of rotational dynamics, the presence of an internal liquid ocean layer allows for differential librations. The libration of Europa's shell remains, however, coupled to the libration of the deep interior through gravitational and pressure coupling torques. Hence, the $z-$components of the linearized Liouville equations for the shell and the mantle are coupled to each other and can be expressed as

$$C^s \Omega \, \dot{m}_z^s = -\dot{c}_{zz}^s \Omega + \Gamma_z^s, \quad (1)$$
$$C^m \Omega \, \dot{m}_z^m = -\dot{c}_{zz}^m \Omega + \Gamma_z^m, \quad (2)$$

where C is the principal axial moment of inertia, c_{zz} is the corresponding small inertia increment, Ω is the mean angular velocity of the body, m_z denotes the excited variations in the spin rate, and Γ_z is the sum of all external and internal torques acting on the layer. The superscripts s and m refer to the ice shell and the rocky mantle of Europa, respectively. Notice that similar equations could be written for both the liquid core and the ocean, but they are not coupled to the libration dynamics of the shell as a result of the assumed Poincaré flow within internal fluid layers [5].

The introduction of (visco-)elastic deformation into the libration dynamics leads to non-zero inertia increment terms and additional terms in the definition of internal coupling and external torques. Explicit expressions for these terms are presented in [4]. Altogether, deformation enhances internal coupling between the mantle and the shell and counteracts the external gravitational torque. Hence, we expect that deformation will tend to reduce the amplitude of the shell's libration relative to the rigid case.

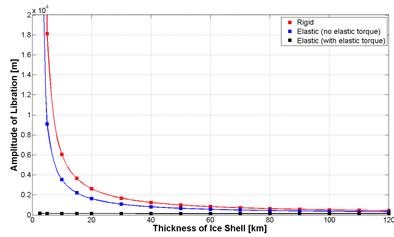

Figure 1: Surface Librations of Europa's shell at the equator.

3. Results

Application of our libration model to the interior models of Europa used in [3], leads to the curves shown in Fig. 1 for different assumptions regarding the rheological properties of the internal layers. The red curve represents the libration of the shell in the rigid case. This curve, as expected, is in full agreement with results from previous research on the rigid librations of Europa's shell [1].

If the internal solid layers are considered to behave nearly elastically, we observe from Fig. 1 that the amplitude of the shell's libration has been considerably reduced for all analyzed values for the thickness of the ice shell. The large difference is mainly due to the effect of elastic deformation on counteracting the external gravitational torque by Jupiter. As can be better observed in Fig. 2, the amplitude of the shell's librations at the surface in the nearly elastic case would range between 125 m for a very thick shell and 161 m for an extremely thin shell. This range of values is close to the value that would be obtained for a rigid Europa without differential librations (red curve).

Introducing viscoelastic relaxation into the modeling would reduce the amplitude of the surface librations even further. For ice viscosities typical for convection, the libration of the shell would become even smaller than the libration of the mantle (magenta curve in Fig. 2). This can be explained by the fact that for low viscosities the ice shell starts to approach fluid behavior even at the aforementioned orbital frequency.

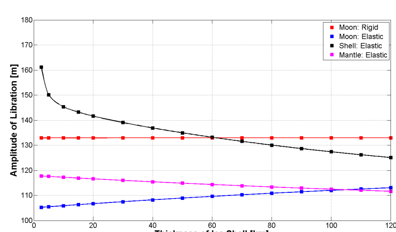

Figure 2: Surface Librations of Europa's shell at the equator.

Acknowledgements

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