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The forced libration of Europa's deformable shell and its dependence on interior parameters

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ABSTRACT

One of the most important goals of future missions to jovian moon Europa will be to unambiguously determine and characterize the putative subsurface ocean, as well as characterizing the overlying ice shell. In addition to magnetic, altimetry and gravity measurements, observations of Europa's librations are expected to contribute to the realization of such an important goal. The longitudinal libration of Europa's shell in the presence of a subsurface ocean has been previously studied assuming that Europa's internal solid layers behave rigidly. However, at the frequency of the acting diurnal tides and external gravitational torques, the response of Europa's interior is not rigid but rather viscoelastic. In this paper, we develop a differential libration model that takes into account the effect of diurnal deformation on the forced longitudinal libration of Europa's internal solid layers. We apply our libration model to a rather large range of possible interior models of Europa to investigate the dependence of the shell libration amplitude on the geophysical parameters that characterize the interior of Europa, in particular the shell. From all analyzed interior parameters, we find that the poorly constrained rigidity of the shell has the largest effect on the libration amplitude. This results suggests thus that future libration observations could be very useful to constrain the value of this parameter for Europa. However, we also notice that the effect of the viscosity of a dissipating ice sublayer at the bottom of the shell (if present) on the libration amplitude of the shell would not allow for an unambiguous determination of the shell rigidity. Furthermore, the dependence of the shell libration amplitude on the shell thickness and density is rigidity-dependent and weak in comparison to the dependence on the rigidity. As a result, libration observations would not be able to provide any information on the thickness and/or density of the shell without previous determination of the rigidity.

1. Introduction

Several different observations made by Voyager and Galileo strongly suggest the existence of a subsurface ocean below Europa's ice shell. Among these observations, the strongest case is made by Galileo's detection of an induced magnetic field, which requires the existence of an electrically conductive layer at shallow depth, most probably a salty ocean (Khurana et al., 1998; Kivelson et al., 2000). Furthermore, imaging of Europa's surface has revealed the presence of arcuate features, commonly known as cycloids, which are thought to have formed due to the effect of diurnal tidal stresses. Since diurnal stresses are expected to become large enough to crack the ice only if a subsurface ocean is present, the existence of these unique features on Europa's surface provides a strong geological evidence for the presence of the internal ocean (Hoppa et al., 1999; Lee et al., 2005; Hurford et al., 2007; Rhoden et al., 2010). In addition, the existence of a subsurface ocean is strongly supported by theoretical models dealing with the thermal state and evolution of Europa's interior (e.g. Ojakangas and Stevenson, 1989; Hussmann et al., 2002; Tobie et al., 2003; Hussmann and Spohn, 2004).

Despite the compelling evidence, the presence of a subsurface ocean has not yet been unambiguously determined. If present, both the ocean and the overlying ice shell will need to be characterized in order to assess the habitability potential of Europa's ocean. In order to reach this goal, several mission objectives have been proposed, such as the characterization of the magnetic field in the vicinity of Europa, the measurement of radial displacements and gravity perturbations as a result of the acting diurnal tides, and the determination of the amplitude of forced longitudinal librations (Van Hoolst et al., 2008; Baland and Van Hoolst, 2010). Although the fulfillment of any of these mission objectives has the potential to confirm the existence of a subsurface ocean on an individual basis, the characterization of the thickness of both the ocean and the overlying ice shell would require an observation

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strategy that combines all of these objectives (see e.g. Grasset et al., 2013, for the aimed strategy for JUICE's characterization of Ganymede's ocean and ice shell).

In this paper, we focus on studying the relation between the amplitude of Europa's forced longitudinal libration at orbital frequency and the geophysical parameters that characterize Europa's ocean and ice shell. The forced libration at orbital frequency is defined as a small periodic variation in the spin rate of Europa driven by the gravitational torque exerted by Jupiter on the triaxial figure of the satellite. Although forced librations occur at different frequencies, we consider here only the main libration at orbital frequency because (a) only short-periodic librations depend on the internal structure of the satellite, and (b) the libration at orbital frequency is around two orders of magnitude larger than other short-periodic librations (Rambaux et al., 2011; Van Hoolst et al., 2013).

Due to the presence of an internal ocean, Europa's outer shell and deep solid interior may perform differential librations which are coupled to each other mainly through gravitational and pressure torques (Baland and Van Hoolst, 2010). Considering that internal solid layers are rigid, previous models of Europa's differential libration infer that the amplitude of the shell libration decreases exponentially with increasing ice thickness (Van Hoolst et al., 2008; Baland and Van Hoolst, 2010; Rambaux et al., 2011). For example, Baland and Van Hoolst (2010) estimates that the amplitude of the shell libration would range between 500 m (for a 100 km thick shell) and 40,000 m (for a 5 km shell). This range of values for the libration amplitude is substantially larger than the $\sim$133 m predicted for the libration amplitude of an entirely rigid Europa (Comstock and Bills, 2003; Van Hoolst et al., 2008; Rambaux et al., 2011). However, Europa's internal solid layers, in particular the ice shell, are not expected to behave rigidly but rather elastically in response to the acting diurnal tides and the librations themselves (Goldreich and Mitchell, 2010). Using a thin shell approach, in which the shell behaves elastically and all internal layers below the shell are assumed to be fluid, Goldreich and Mitchell (2010) reaches the conclusion that elastic effects would considerably diminish the amplitude of the shell libration to $\sim$400 m (independent of the shell thickness). However, due to their assumptions regarding the internal configuration of Europa, the libration model of (Goldreich and Mitchell, 2010) neglects the effect of internal coupling between the shell and the solid interior below the ocean. A current differential libration model of Europa that treats both the ice shell and the deep interior as elastic layers is extensively described in Van Hoolst et al. (2013).

Treatment of the ice shell and silicate mantle as elastic material layers, or even as viscoelastic layers, has been common in studies concerning Europa's diurnal tidal response (i.e. Love numbers) and the corresponding deformations and stresses (e.g. Greenberg et al., 1998; Moore and Schubert, 2000; Wu et al., 2001; Tobie et al., 2005; Harada and Kurita, 2006; Wahr et al., 2009; Rhoden et al., 2010; Jara-Orué and Vermeersen, 2011). Here, we apply the viscoelastic Love number framework to include viscoelastic effects into the libration dynamics of Europa's shell and mantle. The importance of viscoelasticity on the response of a layer to tidal and libration forcing depends on the ratio Δ of the inverse Maxwell time τ_M of the layer ($\tau_M = \eta/\mu$, where η is the layer's viscosity and μ is its rigidity) to the orbital frequency or mean motion n ($n = 2.05 \times 10^{-5}$ rad/s for Europa), i.e. on the ratio $\Delta = \mu/(\eta n)$ (Sotin et al., 2009; Wahr et al., 2009; Jara-Orué and Vermeersen, 2011). If the Maxwell time of a layer would be much larger than the orbital period (i.e. $\Delta \ll 1$), the material layer will behave effectively elastic in response to the applied tidal forcing. On the other hand, if the Maxwell time would be much smaller than the orbital period (i.e. $\Delta \gg 1$), the layer will behave as a fluid. Viscoelastic effects are largest around $\Delta = 1$, which is a ratio expected for the bottom part of a convecting ice shell (e.g. Tobie et al., 2003; Sotin et al., 2009).

The plan of this paper is as follows. In Section 2 we provide a detailed description of our developed libration model. We start in Section 2.1 by defining the general equations governing the libration dynamics of a differentiated interior representative for Europa's internal structure in the presence of an ocean. Thereafter, in Sections 2.1, 2.2, 2.3, 2.4 and 2.5, we introduce viscoelastic deformation to the rotational dynamics by defining analytical expressions for the relevant inertia increments, internal coupling torques and acting external torques. Our complete libration model, which is summarized in Section 2.6, is then applied in Sections 3 and 4 to a range of plausible interior models of Europa in order to study the dependence of the amplitude of the shell libration on geophysical parameters such as the shell thickness, shell density, ocean density, ice rigidity and ice viscosity. Finally, in Section 5, we discuss our results and compare them with the findings of previous libration models, mainly the ones of Van Hoolst et al. (2013).

2. Rotational dynamics

2.1. Longitudinal librations

Europa's spin rate is not uniform but experiences small periodic variations, or longitudinal librations, largely caused by the time-dependent gravitational torque exerted by Jupiter on Europa's non-spherical (triaxial) shape. Depending on the internal structure of Europa, these rotational variations may or may not be the same throughout the interior. In our case, in which we consider the existence of a subsurface ocean between Europa's ice shell and rocky mantle, internal layers may perform differential rotational variations. However, this does not imply that the rotational variations experienced by a layer are decoupled from the ones experienced by other layers, because they remain coupled to each other through gravitational, pressure, viscous and electromagnetic torques (Van Hoolst et al., 2008; Baland and Van Hoolst, 2010). Hence, the determination of the librations experienced by Europa's shell requires the simultaneous determination of the librations of other internal layers.

Since rotational variations and inertia increments are expected to be small, the modeling of longitudinal librations is based solely on the z-component of the linearized Liouville equations (e.g. Munk and MacDonald, 1960; Van Hoolst and Dehant, 2002; Sabadini and Vermeersen, 2004; Van Hoolst, 2007). For a given material layer l, this component of the linearized Liouville equations can be expressed as (Van Hoolst, 2007)

$$C^l \Omega \dot{m}_z^l = -\dot{c}_{zz}^l \Omega + \Gamma_z^l, \tag{1}$$

where C^l is the principal axial moment of inertia of the layer, c_{zz}^l is the corresponding small inertia increment, Ω is the mean angular velocity of the body (equal to the mean motion n for synchronous natural satellites), m_z^l denotes the excited variations in the spin rate, and Γ_z^l is the sum of all external and internal torques acting on the layer. Furthermore, the dot on top of c_{zz}^l and m_z^l stands for their derivative to time.

Although Eq. (1) holds for both solid and fluid layers, a more convenient expression can be used for fluid layers when the flow within these layers is approximated as a uniform vorticity or Poincaré flow (Poincaré, 1910). This Poincaré approximation has been previously employed in the study of rotational dynamics of fluid layers to model the flow in Earth's fluid outer core (e.g. Mathews et al., 1991; Dehant et al., 1993; Greff-Lefftz et al., 2000) and in the putative subsurface oceans and assumed liquid cores of the Galilean satellites (Baland and Van Hoolst, 2010). Based on the