Documentation for files accompanying Rhoden et al. (2021), "Obliquity, precession, and fracture mechanics: Implications of Europa's global cycloid population", published in JGR - Planets

Data files:

The file "Cusps2020_data.cvs" includes data obtained from or calculated through our cycloid mapping.

- "Cycloid Nu" is a unique identifier for each cycloid, which is consistent for all cusps along that cycloid.
- "Id" is the number assigned to each cusp along a given cycloid. The "Id" restarts at 1 for each cycloid whereas "Cusp_ID" is a running total of all measured cusps. Each "Id" (or "CuspID") should have two measurements, one on either side of the cusp. Cusps with multiple branches will have additional measurements on one side of the cusp (see Rhoden et al., 2021 for details). Cusps along each cycloid were mapped from left to right for east-west trending cycloids and top to bottom for north-south trending cycloids. The right side of a cusp was always measured first, followed by the left.
- The "Confidence" ranges from 1 to 3, with 1 being most confident. Poor image resolution or foreshortening contributed to lower confidence ratings. We did not exclude lower confidence features from our analysis.
- "CompassA" is the azimuth of the line segment drawn along the fracture on each side of each cusp.
- "Lat_dd" and "Long_dd" are the coordinates at the end point of the line segment in decimal degrees. Coordinates are given here in east longitude but shown in our maps in west longitude as per the mapping convention for Europa.

The file "interpolatedStress.csv" includes both observational data for each cusp and the output of the tidal stress calculations at each cusp location for comparison between the tidal model and the data. These calculations were made with interior structure 1 (the reference model of Jara-Orue and Vermeersen, 2011), the current eccentricity (using 0.0094 for consistency with J-O&V2011, although we typically use the value 0.01), 85 time steps per orbit, and zero obliquity or non-synchronous rotation for this data file.

- "lat" and "lon" are the coordinates of the cusp. Here, "lon" is given in west longitude to match the tidal stress calculations and for mapping purposes.
- "Id", "cycloid_num", and "cusp_ID" are from the original observation data file, as defined above.
- "Orientation_original" is the orientation measurement, which matches "CompassA" in the observation data file.
- Due to the nature of orientation measurements, any value modulo 180° will yield the same result (e.g., 90° and 135° are the same). The tidal stress calculations give orientation in degrees from 180 to 360°. In "orientation_translated", we have added 180° to any measurement below 180° in order to compare the model output with the observations.
- "Stress" is the tensile tidal stress (kPa) that would produce the observed orientation if failure occurred at that time/magnitude of stress. "Max stress" (kPa) is the largest tensile tidal stress at

any point in the orbit. Stresses are calculated at the location of the end point of each cusp segment. The stress is interpolated along a curve of orientation versus stress to match the observed cusp orientation. See Rhoden et al. (2021) and/or documentation within the accompanying python notebook for details on the procedure.

- "Slope" determines whether the stress in increasing, decreasing, or the same at the point in time when the observed orientation can be reproduced by the tidal stress model. For realistic assumptions about failure, we require the stress be either increasing or flat (slope >= 0) or that the stress magnitude is within 10% of the max stress. If "slope" meets the criteria of >=0, the column "is_increasing" shows TRUE. The remaining slope columns were not ultimately used in our analysis.
- "cusp" direction is the side of the cusp on which the orientation measurement was made. When evaluating stress conditions along a cycloid, all cusps must be matched on the same side (e.g. all the right side measurements can be matched with the tidal model) to be considered a successful fit.

The file "interpolatedWithOblqStress.csv" includes both observational data for each cusp and the output of the tidal stress calculations for comparison between the tidal model and the data. We used the same parameters listed for the previous data file except we made calculations with obliquity values of 0.25° and 0.5° and spin pole directions of 0° to 330° in increments of 30°.

- There are only two additional columns as compared with the no obliquity case: "phase", which is the spin pole direction, and obliquity. This data file is much larger, though, because each right and left measurement for each cusp is listed 24 times (2 obliquity values times 12 SPDs).

Notebooks/code files:

StressEQs.py

This python code contains functions for computing tidal stresses based on the formulation of Jara-Orue and Vermeersen (2011). Stresses depend on the strengths of normal modes, which were computed for two interior structures using an independent code by Wade Henning (wade.g.henning@nasa.gov). The interior structures follow the reference model of J-O&V2011. Structure 1 has a ductile ice viscosity of 1E14 Pa*s, while structure 2 has a more elastic lower ice layer, with a viscosity of 1E17 Pa*s. Both have a 30 km ice shell separated into a 5km brittle layer and a lower viscosity lower layer. Parameter descriptions and units are listed within the code comments.

CycloidCuspAnalysis_Rhoden2021.ipynb

This python notebook contains three sections: 1) data import and calculations of angles, 2) stress calculations and interpolation to determine failure stress implied by the observations, and 3) analysis of matches between observations and stresses for a predetermined set of parameters.

The first four boxes should always be executed as they include import statements that are critical for the rest of the code and they import the observational data. The data file(s) used in the code need to be in the same folder as the notebook, or the paths within the code need to be altered to match the locations of the data files. To reproduce our cups orientation matching results, only Section 3 is required, using the provided data files. The analysis is separated into obliquity and no obliquity sections because the latter only has one left and right entry per cusp, so the analysis is much simpler. If Section 2 is used (see below), StressEQs.py will also be required.

Section 2 allows the user to define parameters with which to compute tidal stresses and identify the inferred failure stresses needed to match the observed cusp orientations. There are two interior structure options, as described above. Eccentricity and obliquity can be varied, as well as the number of time steps in the orbit. Stress from non-synchronous rotation (NSR) can only be computed for interior structure 1. Use of NSR stress is not recommended for this analysis because the interpolation routine expects a curve of orientation versus stress magnitude in which each orientation appears only once, and moves smoothly between 180° and 360°. With NSR, the curves are not always well-behaved, and such contingencies have not been dealt with in the code. Additional details as to the parameter definitions, units, and usage are included within the code comments.