30 Rotational Motions in Seismology: Theory, Observation, Simulation

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30.1 Introduction

The rotational part of earthquake-induced ground motion has basically been ignored in the past decades, compared to the substantial research in observing, processing and inverting translational ground motions, even though there are theoretical considerations that suggest that the observation of such motions may indeed be useful and provide additional information. In the past years, interest in this potentially new observable for seismology has risen, primarily because – with modern acquisition technology such as fiber-optical or ring laser gyros – rotational motions have actually been observed, the resolution is steadily increasing, and the observations are becoming consistent with collocated recordings of translational ground motions. Even though the real benefit to Earth sciences is still under investigation, recent results suggest that collocated measurements of rotations and translations may allow the estimation of wavefield properties (such as phase velocities, direction of propagation) that otherwise can only be determined through array measurements or additional strain observations. In this paper we focus on studies of the vertical rotational component (twist, spin, or rotation around a vertical axis) and review recent results on the fundamental concepts that are necessary to understand the current broadband observations of a wide distance and magnitude range, and show that the classical theory of linear elasticity is sufficient to explain these observations. In addition to direct measurements of rotational motions using ring laser technology, we describe the method to derive rotational motions from seismic arrays and present some initial results. Sophisticated 3D modelling of the rotational ground motions of teleseismic events illustrate the accuracy with which observed horizontal phase velocities match with theoretical predictions, even though the precise waveforms are quite different due to inaccuracies in crustal models or kinematic rupture properties. This may have implications for sparse networks or situations where extremely few or even single-station observations are taken (e.g., in remote areas or planetary seismology).

To fully characterize the motion of a deformable body at a given point in the context of infinitesimal deformation, one needs three components of translation, six components of strain, and three components of rotation, a vectorial quantity. Rotational motions induced by seismic waves have been essentially ignored for a long time, first because rotational effects were thought to be small (Bouchon and Aki 1982), and second because sensitive measuring devices were not available. Indeed, Aki and Richards (1980, p. 489) point out that *the state-of-the-art sensitivity of the general rotation sensor is not yet enough for a useful geophysical application*.

However, there have been many reports of rotational effects associated with earthquakes (like twisting of tombstones, or statues). It is certainly possible that some of these effects are due to the asymmetry of the construction. Indeed, as is well known, when the center of mass is not located at the geometric center, a mere translation may induce a local rotation of that structure. However, some field evidences suggest that it is at least not always the case (Galitzin 1914, p. 172). The rotational angles calculated by Bouchon and Aki (1982) for realistic cases of earthquake scenarios (about 10^{-4} radians) seem indeed too small to be responsible for damages, except, maybe for the case of long structures. However, as, roughly speaking, rotations are proportional to displacement divided by the phase velocity (see Section 30.2.3), when the wave velocity becomes smaller, rotations become comparatively larger. This happens in soft or unconsolidated sedimentary and/or fluid-infiltrated porous media, where wave speeds might be as low as about 50 m/s, hence smaller than usual by about a factor of 50. Thus, it is not implausible that, near seismic sources – where rotations and strains become relatively large even in normal media – rotations and strains become really large and be responsible for the above mentioned damages (there is also growing seismological evidence that rotational amplitudes have been underestimated (Castellani and Zembaty 1996)). Obvi-