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Network sensor calibration for retrieving accurate moment tensors of acoustic emissions

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ABSTRACT

We apply a method for retrieving accurate moment tensors in the acoustic emission (AE) experiments based on the joint inversion of a family of AE events for their moment tensors and for the sensor amplifications including coupling effects between sensors and a specimen. The accuracy and efficiency of the method is tested on AEs recorded during three different temporal stages of a triaxial compression experiment on a cylindrical Bentheim sandstone specimen. The results show improved quality of the moment tensors indicated by significantly lower root-mean-square residuals between observed and predicted amplitudes. The approach is particularly suitable for detailed studies of the source parameters of AE events, to obtain accurate focal mechanisms and seismic moment tensors and for detecting fracturing regime of microcracks.

1. Introduction

Moment tensor inversion is one of the basic tools for analyzing source mechanisms of tectonic and volcanic earthquakes observed in the Earth's crust, but also of acoustic emissions (AEs) recorded in laboratory environments [1–8]. Although AEs and earthquakes are different in size and radiated frequencies, the physics of the source and the source mechanisms are basically similar and the moment tensors can provide insights into fracture processes on all these scales. The double-couple (DC) and non-double-couple (non-DC) components of the moment tensors are, in particular, important when studying: (1) the orientation and geometry of micro-cracks, cracks, fractures or faults, (2) physical properties of rocks in the focal zone, and (3) the shear/tensile type of fracturing [9–11]. In addition, the moment tensors provide valuable information on the stress field in the focal zone.

Similarly as for earthquakes, moment tensor inversion of AEs is a data-demanding procedure which requires an accurate velocity model, accurate locations and high-quality data with a high signal-to-noise ratio, recorded by many sensors with good azimuthal coverage. In earthquake seismology, the difficulties in the moment tensor inversion usually arise because of unfavorable station configurations and inaccurate and simplistic velocity models used, which can produce numerical errors in the inversion. In contrast to observations of earthquakes, the velocity model can be measured quite accurately in AE experiments and also the configuration of sensors can be designed to be optimum. However, we often meet with a problem of poorly known amplitudes of recordings when inverting AEs because the sensor calibration is often inaccurate and/or the coupling effects between the sensors and the specimen are usually neglected. Since measuring correct amplitudes is a key factor in determining accurate moment tensors, this problem must be addressed and solved in all advanced studies of acoustic emissions.

Recently, a new method which solves the problem of the sensor calibration was proposed by Davi and Vavryčuk [12] and tested on seismic data. The method is called the network calibration and it is based on a joint inversion of a family of seismic events for their moment tensors and for sensor amplifications. The method proved to be an efficient way to determine or to correct the sensor amplifications in order to retrieve highly accurate moment tensors of earthquakes. In this paper, the method is applied to AE data at a laboratory scale. The results show an improved quality of the retrieved moment tensors indicated by significantly lower root-mean-square (RMS) residuals between observed and predicted amplitudes if the network calibration is performed. The improvement of accuracy is particularly visible when analyzing the non-DC components of the moment tensors, which are important for interpretations and understanding of source processes [9,11,13–16].

2. Method

The standard moment tensor inversion of amplitudes for one individual event is based on the following equation:

$$\mathbf{G}\,\mathbf{m} = \mathbf{u}, \tag{1}$$

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where $\mathbf{G}$ is the Nx6 matrix of the spatial derivatives of the Green's function amplitudes,

$$\mathbf{G}=\begin{bmatrix}\mathbf{g}^{(1)}\\ \mathbf{g}^{(2)}\\ \cdots\\ \mathbf{g}^{(N)}\end{bmatrix}=\begin{bmatrix}G_1^{(1)} & G_2^{(1)} & G_3^{(1)} & G_4^{(1)} & G_5^{(1)} & G_6^{(1)}\\ G_1^{(2)} & G_2^{(2)} & G_3^{(2)} & G_4^{(2)} & G_5^{(2)} & G_6^{(2)}\\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots\\ G_1^{(N)} & G_2^{(N)} & G_3^{(N)} & G_4^{(N)} & G_5^{(N)} & G_6^{(N)}\end{bmatrix}, \quad (2)$$

$\mathbf{m}$ is the vector composed of 6 components of moment tensor $\mathbf{M}$,

$$\mathbf{m}=\begin{bmatrix}M_{11} & M_{22} & M_{33} & M_{23} & M_{13} & M_{12}\end{bmatrix}^T, \quad (3)$$

and $\mathbf{u}$ is the vector of displacement amplitudes observed at N one-component sensors. Quantities $G_k^{(i)}$ are the components of the Green's function matrix for the ith sensor

$$G_1=G_{1,1}, G_2=G_{2,2}, G_3=G_{3,3} \quad (4)$$

$$G_4=G_{2,3}+G_{3,2}, G_5=G_{1,3}+G_{3,1}, G_6=G_{1,2}+G_{2,1} \quad (5)$$

where $G_{k,m}$ means the spatial derivative of the Green's function produced by the force along the k-axis and oriented along the sensor direction. The superscript i identifying the sensor is omitted.

If we incorporate one sensor of an unknown amplification with index $i=N+1$ into the inversion, we can put

$$\mathbf{g}^{(N+1)}\mathbf{m}=C^{(N+1)}u^{(N+1)}, \quad (6)$$

where $C^{(N+1)}$ is the unknown amplification, and $\mathbf{g}^{(N+1)}$ is defined as follows:

$$\mathbf{g}^{(N+1)}=\begin{bmatrix}G_1^{(N+1)} & G_2^{(N+1)} & G_3^{(N+1)} & G_4^{(N+1)} & G_5^{(N+1)} & G_6^{(N+1)}\end{bmatrix} \quad (7)$$

Combining Eqs. (1) and (6) we obtain the following equation for moment vector $\mathbf{m}$ and amplification $C^{(N+1)}$:

$$\begin{bmatrix}\mathbf{G} & \mathbf{0}\\ \mathbf{g}^{(N+1)} & -u^{(N+1)}\end{bmatrix}\begin{bmatrix}\mathbf{m}\\ C^{(N+1)}\end{bmatrix}=\begin{bmatrix}\mathbf{u}\\ 0\end{bmatrix} \quad (8)$$

Obviously, a similar system of equations can be written for the inversion for moment tensors of many events and for the amplifications of many sensors [12]. For illustration, if ten events recorded at ten sensors with known amplification are inverted for moment tensors, the joint inversion is based on solving a system of one hundred equations for 60 unknowns that is a well overdetermined problem. If ten events recorded at one sensor with known amplification and at nine sensors of unknown amplification are inverted for moment tensors and amplifications, a system of one hundred equations is solved for 69 unknowns that is still an overdetermined problem. In principle, it is permissible that all sensors are of unknown amplification and we can still invert for moment tensors and for the sensor amplifications. In this case, however, the inversion yields the relative moment tensors and the relative sensor amplifications only. The scalar moments and the absolute sensor amplifications cannot be determined.

As for the standard moment tensor inversion, the joint inversion works properly if the following conditions are satisfied: (1) the network of sensors must ensure a dense coverage of the focal sphere, (2) amplitudes of events must have a good signal-to-noise ratio, (3) the propagation velocity within the specimen must be known with the highest accuracy as possible, and (4) event locations must be accurate. In addition, extensive datasets of events, displaying a variety of focal mechanisms, are required so as the system of equations to be well overdetermined. In order to increase the accuracy of the amplifications, the inversion can be performed in iterations (for details, see [12]). In this case, the sensor amplifications are calculated repeatedly with gradually increasing accuracy. If the difference between the amplifications from the previous and the current iterations are less than a prescribed error, the iteration process is stopped. If no sensor amplification is known before the calibration, the average of the sensor amplifications must be fixed in the inversion.

3. Experiment setup and AE hypocentre locations

The method is exemplified on acoustic emissions recorded during a triaxial compression experiment carried out at the GFZ Potsdam. The experiment was performed on a cylindrical Bentheim sandstone specimen (50 mm diameter and 105 mm in length) with a notch in its mid-height. The specimen was initially loaded under isotropic compression (up to 160 MPa confining pressure) and subsequently under deviatoric compression (with a displacement control at a rate of 20 μm/min) up to almost 1.2% of axial strain, before being fully unloaded. Compaction bands were formed in this specimen, alike what has been also observed in other porous sandstones being subjected to similar stress states [17,18]. A detailed description of the experimental results as well as the formation and evolution of the developed compaction bands is not the subject of this paper and it will be published in another paper.

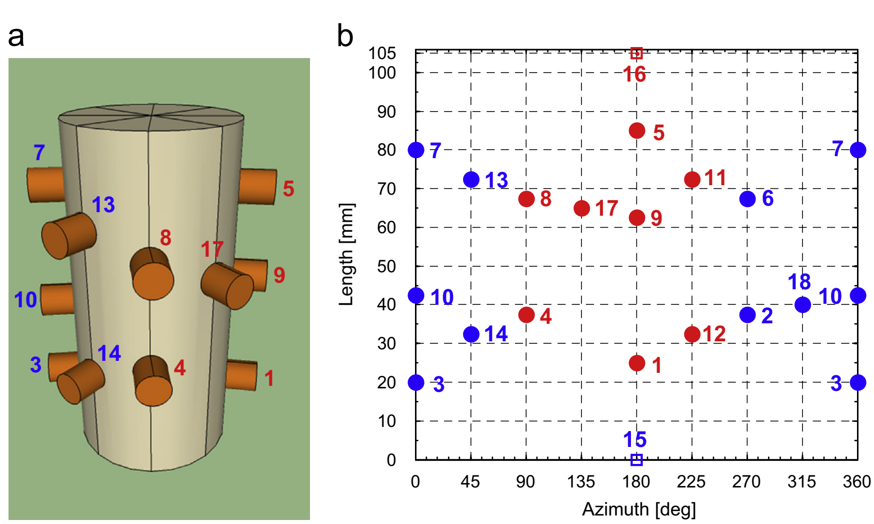

Fig. 1. (a) Schematic plot of the positions of the AE sensors glued on the surface of the Bentheim specimen; (b) Azimuthal coverage of AE sensors used as receivers (in blue) and as receivers and transmitters (in red) as a function of the length of the specimen.