ORION-AE: MULTISENSOR ACOUSTIC EMISSION DATASETS REFLECTING SUPERVISED UNTIGHTENING OF BOLTS IN A JOINTED VIBRATING STRUCTURE

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ABSTRACT

Monitoring loosening in jointed structures during operation is challenging because contact and friction, in bolted joints, induce a nonlinear stochastic behavior. The purpose of work is to provide datasets from acoustic emission (AE) sensors obtained during harmonic vibration tests. These datasets have been used to validate the development of a new clustering method for time-series, based on an original loss function that includes parameters on clusters onset, kinetics and accumulation [3]. The datasets are originating from a jointed structure called ORION, which is an original test-rig designed for vibration study. It integrates several sensors that provide the vibration velocity from a laser vibrometer and the acoustic signals from three different AE sensors. A design of experiment allowed to acquire data streams in different operating conditions by varying the tightening configurations. These datasets can be used to challenge machine learning and signal processing methods.

Keywords  ·  bolted joints  ·  health monitoring  ·  acoustic emission  ·  laser vibrometry
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Specifications Table

| Subject | Structural Analysis and Behavior |
|---------|----------------------------------|
| Specific subject area | Structural health monitoring, condition-based monitoring, time-series modelling |
| Type of data | Time-series |
| Figure | |
| How data were acquired | Acoustic emission sensors micro80, F50A, micro200HF |
| | Picoscope 4824 with MATLAB Data Acquisition Toolbox |
| | Tira TV5120, electromagnetic shaker |
| | PCB 208C02 piezoelectric force sensor |
| | Polytec PSV 500 XTRA laser vibrometer |
| Data format | Raw |
| Parameters for data collection | Sampling frequency: 5 MHz on four channels (acoustic emission sensors and vibrometer) |
| | Tightening level set by a torque screwdriver after three checks of the value (60, 50, 40, 30, 20, 10 and 5 cNm) |
| | Shaker frequency: 100 Hz |
| | Preamplifier set to 60 dB for the three acoustic emission sensors |
| | Control of the load applied by the shaker according to the displacement of the top plate measured by the laser vibrometer and maintained fixed for all tightening levels |
| Description of data collection | The shaker was started after setting the tightening level and stopped after 10 seconds before changing the tightening level to the next value. One series of measurements consists in applying seven different tightening levels. |
| Data source location | Institution: FEMTO-ST institute, Department of Applied Mechanics |
| | City/Region: Besançon, Bourgogne-Franche-Comté |
| | Country: France |
| Data accessibility | Repository name: Harvard Dataverse |
| | Data identification number: 10.7910/DVN/FBRDU0 |
| | Direct URL to data: [https://doi.org/10.7910/DVN/FBRDU0](https://doi.org/10.7910/DVN/FBRDU0) |
| Related research article | This DIB paper is a co-submission related to the following work [3] |
| | Authors: Emmanuel Ramasso, Thierry Denœux and Gaël Chevallier |
| | Title: Clustering acoustic emission data streams with sequentially appearing clusters using mixture models |
| | Journal: Mechanical Systems and Signal Processing |
| | Status: In Press |

Value of the Data

- Experiments were designed to reproduce the loosening phenomenon observed in aeronautics, automotive or civil engineering structures where parts are assembled together by means of bolted joints. The bolts can indeed be subject to self-loosening under vibrations. Therefore, it is of paramount importance to develop sensing strategies and algorithms for early loosening estimation [6]. The test rig was specifically designed to make the vibration tests as repeatable as possible and allowed us to generate a set of time-series collected from different acoustic emission sensors and a laser vibrometer.

- Acoustic emission datasets are generally processed using unsupervised learning algorithms because it is not possible to identify the acoustic emission source with certainty. With the ORION-AE time-series datasets, we know that, during each period of 10 seconds, the tightening level has been set to a specific value and therefore can be used as a reference. ORION-AE datasets can thus be used to train supervised (deep/transfer) learning methods (with possibly 7 classes). It can also be used for unsupervised or semi supervised learning [3], using the tightening levels as a reference to be compared with, using, for example, the Adjusted Rand Index [5]. With the use of three different acoustic emission sensors as well as laser vibrometer measurements, multisensor data fusion can be performed.

- The sensors used, with different frequency bands, are expected to detect the stick-slip transitions or shocks in the interface that are known to generate small AE events during vibrations. The acoustic waves generated by these events are highly dependent on bolt tightening. These sources of AE signals have to be detected and identified from the data stream which constitute a challenge. ORION-AE datasets can thus provide insights, from multiple acoustic emission sensors, about tribological conditions in contacts between plates during vibration tests of jointed structure.

Data Description

The datasets were obtained on a test rig called Orion. It is constituted of a jointed structure, dynamically loaded with a vibration shaker and monitored with acoustic emission, force, and velocity sensors.
Details of the folders and files

For each series of measurements, four sensors were used simultaneously: a laser vibrometer and three different AE sensors (micro80, F50A, micro200HF), each with a given frequency band, all sampled at 5 MHz, yielding approximately between 1.4 and 1.9 GB of data. A total of five series of measurements were performed denoted as measurementSeries_B, measurementSeries_C, measurementSeries_D, measurementSeries_E and measurementSeries_F.

The organization of repositories and files is depicted in Figure 1 for series of measurements B. There is one folder for each series of measurements. The ORION-AE dataset is thus composed of five folders. For each series of measurements, there are seven subfolders corresponding to seven tightening levels: 60, 50, 40, 30, 20, 10, 05 cNm, except for measurementSeries_C for which 20 cNm is missing.

It is important to read the subfolders in this precise order, otherwise the physical meaning of the data becomes wrong. The upper bolt have been untightened with a precise sequence. For example, reading from 5 cNm to 60 cNm (reverse order) does not correspond to the "tightening" of bolts since the process is not reversible in terms of acoustic emission characteristics.

Each subfolder is made of .mat files generated using MATLAB 2014b. There is about one file per second. The files in a subfolder are named according to the timestamps (time of recording). Each file has the following format:

```
salves_out_XcNm_Y_Fs5MHz_Tfs1s_2019-04-02-HH-MM-SS_1.mat
```

where \( X \in \{5, 10, 20, 30, 40, 50, 60\} \) representing the tightening level, \( Y \in \{B, C, D, E, F\} \) for the series of measurements. The production date is "2019-04-02" and the timestamp began at HH-MM-SS. For example,

```
salves_out_05cNm_B_Fs5MHz_Tfs1s_2019-04-02-16-22-09_1.mat
```

represents AE data for 5 cNm in series of measurements B taken at 16:22:09. Each .mat file is composed of vectors of data with the following names:

- Variable "A" corresponding to micro80 sensor data.
- Variable "B" corresponding to F50A sensor data.
- Variable "C" corresponding to micro200HF sensor data.
- Variable "D" corresponding to laser velocimeter data.

The labels corresponding to the sensors must not be confused with the labels corresponding to the test campaigns. Illustrations of the data are given in Figures 2, 3 and 4 for, respectively, sensor "micro80" (variable "A" in a file), "F50A" (variable "B" in a file), "micro-200-HF" (variable "C" in a file), and concerning measurementSeries_B.

It is important to note that the real timestamps in filenames must not be taken as the timestamps of the AE signals in a data stream. The real timestamps must be calculated from the exact number of samples in each file, starting from \( t = 0 \)s for 60 cNm. There are about 10 s of continuous recording of data per level and for the four sensors. The exact duration of a period can be found according to the number of files in each subfolder, the number of points per file and the sampling frequency. The precise values are given in Table 2. A Matlab code (ORION_AE_sample_read_files.m) is provided in the data repository to read the files and reproduce the duration of each period.

| Meas. series | 60 cNm | 50 cNm | 40 cNm | 30 cNm | 20 cNm | 10 cNm | 5 cNm |
|--------------|--------|--------|--------|--------|--------|--------|-------|
| B            | 10.0000| 10.0000| 10.0000| 9.0170 | 10.0000| 10.7725| 9.2275|
| C            | 10.0000| 10.0000| 10.0000| 10.0000| N.A.   | 10.0000| 10.0000|
| D            | 10.0000| 10.0000| 10.8119| 9.1881 | 10.0000| 10.0000| 10.0000|
| E            | 10.0000| 10.0000| 10.0000| 10.0000| 10.0000| 10.0000| 10.0000|
| F            | 10.0000| 10.0000| 10.0000| 10.0000| 10.0000| 10.0000| 10.0000|

Table 2: Duration in seconds of each period for a given tightening level. The exact duration of a period can be found according to the number of files in each subfolder, the number of points per file and the sampling frequency.

About the ground truth and possible challenges in machine learning and signal processing

In ORION-AE datasets, we know that, during each period of 10 s, the tightening level has been set to a specific value. The tightening level can be considered as constant during each period, and therefore can be used as a reference. ORION-AE datasets can thus be used to
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Figure 1: Tree structure of the repositories and files exemplified for series of measurements "B".

- train supervised learning methods (with possibly 7 classes);
- validate unsupervised learning (clustering), using the tightening levels as a reference to be compared with, using, for example, the Adjusted Rand Index [5].

However, it is noteworthy that during each cycle of the vibration test for a given tightening level, different AE sources can generate AE signals and those sources may be activated or not, depending on the tribological conditions. The tightening level may thus slightly change during the 10 seconds period. Therefore the reference is not fully reliable. Results shown in [3] demonstrate that the content of AE signals in those series of measurements is sufficient to discriminate between the periods, which seem to corroborate that the AE sources have indeed a signature depending on the tightening level.

In addition to machine learning tasks, this dataset can be used for signal processing and in particular wave-picking. This term is inherited from seismic wave detection in [1] and represents a way of finding relevant signals in a data stream. Wave-picking is the most important task in acoustic emission analysis because it paves the way for feature extraction, classification, localization of acoustic emission sources and interpretation by machine learning. The ORION datasets has an essential characteristic that makes it practically useful for the validation of wave-picking algorithm: the presence of the vibrometer data. Figure 5 shows the vibrometer data superimposed with the AE stream after applying an algorithm proposed in [2] based on wavelet denoising. This figure shows a number of acoustic emission signals that are repeated at each cycle with quite a good reproducibility in terms of levels of displacement measured by the vibrometer. This figure shows that it is possible to challenge wave-picking algorithms by trying to find either one set of signals per cycle or a set of several signals which should occur at similar displacement level along cycles. The characteristics of those signals may be quite close for a given tightening level and may change between levels [3].

By applying the algorithm proposed in [2] for detecting acoustic emission signals, the onsets of those signals can be superimposed onto vibrometer data as shown in Figure 6. With a first setting, it is possible to get Figure 6a showing about one signal per cycle. This setting was used in [3]. With a second setting, Figure 6a depict about 3 signals per cycle. The vertical position of the onsets of acoustic emission signals clearly demonstrate the high reproducibility of the test rig.
Experimental Design, Materials and Methods

The design of the ORION test rig [4] (Figure 7) is characterized by a vibration damping and make the vibration tests reproducible. It is a jointed structure made of two plates manufactured with 2024 aluminium alloy, linked together by three M4 bolts (Figure 7). Contact patches, i.e. machined overlays, have been added at each bolt connection to retain the contact between both beams in a small area, minimizing uncertainties on the structure’s response and enhancing the repeatability between measurements. The contact patches have an area of $12 \times 12$ mm$^2$ and are 1 mm thick. The
Figure 3: Sample of the data in measurements series "B" with sensor "F50A" for each tightening level.
Figure 4: Sample of the data in measurements series "B" with sensor "micro-200HF" for each tightening level.
Figure 5: Presence of signals in each cycle after wavelet denoising. For a given tightening level, the displacement measured by the vibrometer should be quite close for each signal found at different cycles.
Figure 6: Acoustic emission onsets find by [2] and positioned onto vibrometer data for measurement B, first file in 60 cN.m, sensor "micro-200-HF".
central bolt is dedicated to "static" functions, i.e. to ensure structural integrity and provide resistance to dynamic loads without substantial stiffness changes. The external bolts, in turn, perform "damping" functions, i.e. to increase energy dissipation due to frictional contact. It is worth noticing that these two functions have to be monitored in order to ensure the integrity (central bolt) and the damping (lateral bolts).

The harmonic excitation load was applied using a Tira TV51120, electromagnetic shaker which can deliver a 200 N force. The structure was submitted to a 100 Hz harmonic excitation force during about 10 s. The force was measured using a PCB 208C02 piezoelectric force sensor.

The vibration magnitude was measured using a Polytec PSV500Xtra, laser vibrometer. The obtained laser data allowed us to make sure that the amplitude of the displacement of the top of the upper plate remains constant whatever the tightening level.

Seven tightening levels, corresponding to seven operating conditions of the structure under vibration, were applied on the upper bolt. The tightening level was first set to 60 cNm with a torque screwdriver. After about a 10 s vibration test, the shaker was stopped and this vibration test was repeated after a torque modification at 50 cNm. Then torque modifications at 40, 30, 20, 10 and 5 cNm were applied. The change in the tightening level was made using a CDI torque screwdrivers. The torque was checked three times at each change.

The acoustic emission sensors used were a "micro-200-HF", a "micro-80" and a "F50A", made by Euro-Physical Acoustics. They were connected to a preamplifier set to 60 dB (model 2/4/6 preamplifier made by Europhysical acoustics). Their detailed characteristics, such as dimensions and frequency bands, are provided in the datasheets enclosed in the datasets, with a summary of the main ones given in Table 3. The sensors were attached onto the lower
plate (5 cm above the end of the plate) using a silicone grease. All data were sampled at 5 MHz using a Picoscope 4824 (20 MHz bandwidth, low noise, 12-bit resolution, 256 MS buffer memory, USB 3) connected to a linux PC with MATLAB® 2016b and the Data Acquisition® toolbox. The datasheet of the Picoscope is provided in the dataset.

|                                   | Units | F50A | micro80 | micro200HF |
|-----------------------------------|-------|------|---------|------------|
| Peak Sensitivity, Ref V/(m/s)     |       |      |         |            |
| Operating Frequency Range (kHz)   | kHz   | 200-600 kHz | 200-900 | 500-4500   |
| Resonant Frequency, Ref V/(m/s)   | kHz   | 100 kHz | 250     | 2500       |

Table 3: Frequency and sensitivity of the acoustic emission sensors used. The data sheets are provided in the datasets.

Credit author statement

Benoit Verdin: Data acquisition and curation, software; Emmanuel Ramasso: Data acquisition, software, conceptualization, funding acquisition, project administration, writing - original draft; Gaël Chevallier: Design of the test rig, physical modelling, supervision, conceptualization, funding acquisition.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships which have, or could be perceived to have, influenced the work reported in this article.

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