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Proceeding Paper

Time-Domain Analysis of Acoustic Emission Signals during the First Layer Manufacturing in FFF Process [†]

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Abstract: Additive manufacturing (AM) has been played a crucial role in the fourth industrial revolution. Sensor-based monitoring technologies are essential in detecting defects and providing feedback for process control. Acoustic emission (AE) sensors have been used for long time in a wide range of processes and fields, but they are still a challenge in AM processes. This work presents a study on the AE signals in the time-domain—raw and root mean square (RMS) values—regarding their behavior during the manufacturing of a single-layer part in the Fused Filament Fabrication process for two infill patterns. Tests were conducted in a Cartesian 3D printer using Polylactic Acid material. The AE sensor was attached to the printer table through a magnetic coupling, and the signal was collected by an oscilloscope at 1 MHz sampling frequency. It was found that the raw AE signals behaved quite differently not just for the two infill patterns, but within the same pattern. The raw and RMS AE signals contain many spikes along the whole process, but the higher ones were those generally occurring at the end and/or start of a fabrication line. The RMS values, however, was useful for finding the start and end times of each fabricated line for both patterns. The mean RMS values have shown a nearly constant but distinct averages for the only-extruder, only-table and extruder-table movements.

Keywords: Fused Filament Fabrication; acoustic emission; monitoring; infill pattern

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1. Introduction

Traditional manufacturing processes, such as forging, welding, casting and turning, which were marked by industrial revolution, have brought countless benefits to the world over the years. However, science and practitioners have always been in search for faster processes with a higher level of accuracy, which paved the way to a new type of process, such as the Additive Manufacturing (AM). As one of the pillars of the fourth industrial revolution, AM has arrived to transform the way products are manufactured.

The most widely used and rapidly growing AM technologies are extrusion deposition processes, such as Fused Deposition Modeling (FDM), Fused Filament Fabrication (FFF) and Melt Extrusion Manufacturing (MEM) [1]. At the same time the use of AM has been increasing, lots of challenges such as insufficient level of product quality, robustness material properties and controllability impair its more extensive adoption and commercialization [1,2].

The AM process monitoring is of utmost importance in detecting defects and providing feedback for process control, which is crucial to further understanding the processes, improving process efficiency and quality, and producing parts with desired quality. Therefore, there is a strong need to develop sensor-based monitoring methods to overcome some of these challenges, as process monitoring has proved its effectiveness in numerous other manufacturing technologies [1–3].

Some research works on AM process monitoring based on sensors can be found, which used filament feed speed sensor, borescope camera, MEMS accelerometer, thermocouple and IR temperature sensor [4], and acoustic emission (AE) sensor [1–3]. However, the use of AE sensor is more attractive for monitoring the AM process, since the signals are sensitive to the change of machine and extruded material dynamics during fabrication process, and the sensor usually has a wider range of operating frequencies than other dynamic sensors (e.g., accelerometer) [2].

Thus, this work conducts a study on the acoustic emission signals in the time-domain—raw and root mean square (RMS) values—regarding their behavior during the manufacturing of a single layer part in the FFF process for two infill patterns. It was not found research work on studying the behavior of the AE signals, raw and RMS values, during the first layer fabrication for two distinct infill patterns. The contribution of this paper is to provide additional information about AE signals regarding the FFF process monitoring to the research community and engineers in the AM field with the use of AE sensor, and then help to a better understanding of the process as well as its optimization.

2. Materials and Methods

The tests were conducted in a GTMax3D®, Graber i3 model Cartesian 3D printer. This model is equipped with a MK2B Dual Power PCB table, as well as a NTC 100k thermistor temperature sensor connected to a 200 × 200 × 3 mm glass plate, and a Hotend All-metal GTMax3D model extruder. The following parameters were used: nozzle temperature 190 °C, bed temperature 65 °C, layer height of 300 µm, nozzle diameter of 0.4 mm, fill density of 20%, printing speed of 20 mm/s.

The deposition movement produced by the Graber i3 3D printer is achieved by movement relative to tracks running along the axes. For a printing exclusively along the x-axis, only the extruder moves, and exclusively along the y-axis, only the printing table moves. Consequentially, for a printing utilizing the x and y axes simultaneously, both the printing extruder and table move.

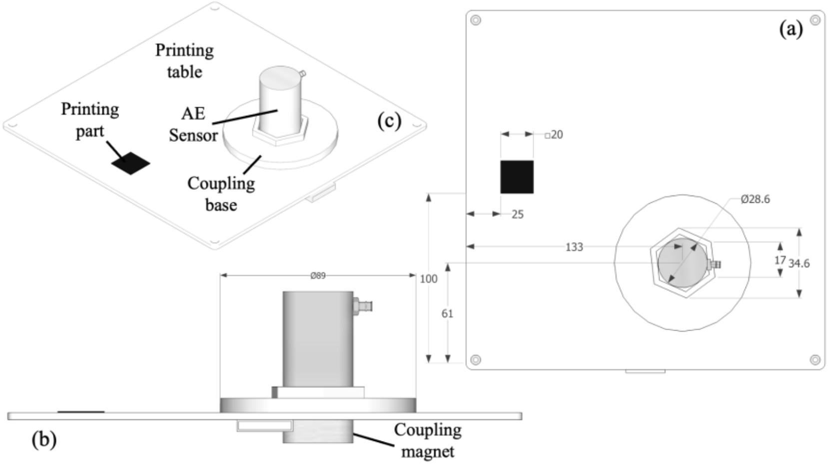

Figure 1. FFF monitoring setup schematic, (**a**) Top view, (**b**) Front view, (**c**) Isometric view.

An AE Physical Acoustics®, R.451 model sensor, with a frequency response of 1 Hz to 20 kHz, was fixed by means of a magnetic base at 133 × 61 mm from the lower left corner of the printing table. To allow coupling between the magnetic base and the glass table, a neodymium magnet was positioned under the printing table.

The glass table temperature was controlled by the heating system of the printer via the Repetier-Host® software. A square part of 20 × 20 × 0.3 mm was designed in three dimensions using the SketchUp® software, which was printed at 25 × 100 mm from the lower left corner of the printing table. The Polylactic Acid (PLA) was the printing material used with a filament width of 1.75 mm.

Figure 1 shows the square part in the defined printing position, and the AE sensor fixed through the magnetic coupling base to the printing table.

The fabrication parameters were the default values of the Slic3r® software, which is part of the Repetier-Host® software. The single layer part consisted of two Infill Patterns, as shown in Figure 2.

The External Infill Pattern (EIP) was used for the fabrication of the external lines, following the movement of the extruder or table in an angle of 0°, 90°, 180° and 270°, while the Internal Infill Pattern (IIP), which started after the EIP had completed, was used for the fabrication of the internal lines, following the directions determined by the 45° raster angle for both extruder and table movements. The external and internal printing patterns are composed of 12 and 32 lines, respectively.

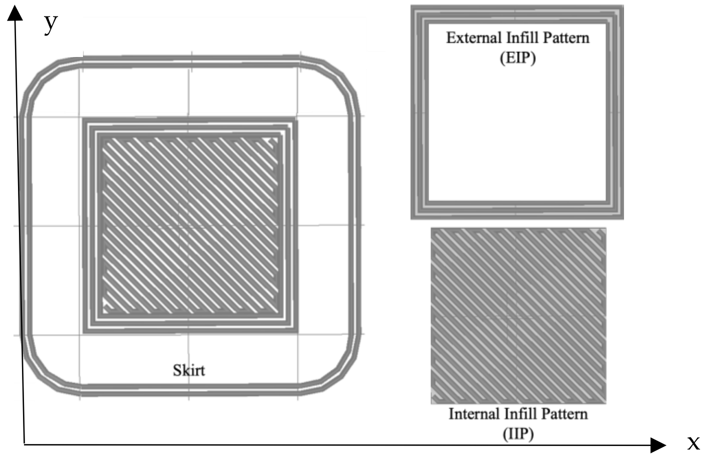

Figure 2. Postprocessed printing part.

The printing process of the part was repeated three times to ensure the consistency and reliability of the measurements. The Yokogawa DL850 oscilloscope was used to collect AE signals throughout the printing process at a sample frequency of 1 MHz; the data was captured and stored on the oscilloscope internal hard drive. The data was digitally processed after the tests using the Matlab® software. The printing processes were recorded with the use of a Motorola smartphone, model Moto G5SPlus in order to help identifying the times of each printing cycle.

The raw AE signals were truncated in order to get only the segments (lines) extracted regarding each infill pattern. The RMS values were computed for each segment for further analysis. It was used the integration time of 1ms for RMS computation. The average RMS and standard deviation values for each segment were then computed. The integration time of 1 ms was adopted based on the reference [5].

3. Results and Discussion

The raw AE signals are shown in Figure 3. The vertical dashed lines in this figure represent the segment fabricated for each pattern, which were found by using the video recorded during the fabrication as well as the RMS signal. From a macro perspective, it can be observed clearly for the EIP the great difference AE amplitudes between the odd (x-axis) and even (y-axis) segments of the signal along the entire fabrication of this infill pattern. This can be explained by recalling Section 2, where it was described that in the x-direction only the extruder moves, whereas in the y-axis only the table moves. There are two step motors of the same specification in charge of these movements. On the other hand, it is known and clearly noticeable that the step motor of the extruder mechanism has a much lighter load than the step motor of the table mechanical apparatus. According to [6], the main source of acoustics is the vibration of the step motors. Also, according to [7], the mechanical structure to which the various stepper motors are attached are different. Variation in the load affects the rotor oscillation and the vibration, whereas the variation in the mechanical structure affects the natural frequencies. Therefore, the greater amplitude of AE signal in the y-axis is due to the greater load of the table mechanical system, in addition to the fusion and deposition process. It is also clearly noticed in this signal the peaks occurring between the odd and even segments, which is due to the complete stop of one step motor (end of a segment fabrication in the x-axis) and the start of the other step motor (beginning of a new segment fabrication in the y-axis), thereby producing a spike of AE.

The raw AE related to the IIP is shown in Figure 3, which starts at 10.92 s approximately. It can be observed for this pattern a very noisy signal, and the segments increasing their sizes from the beginning of this infill pattern fabrication up to the main diagonal segment, and then decreasing the sizes up to the end of the fabrication, as expected. However, the 32-IIP segments are not distinguishable in the signal as in the EIP, and then a micro view of the raw signal, recorded video of fabrication or RMS signal analysis are needed to get the segments definition. The amplitude of the signal varies along the IIP, but it has an average value with less dispersion when compared to the EIP. This is due to the simultaneous movements of the table and extruder systems, whose mechanisms request nearly the same load from the step motors during this pattern fabrication, and then generate a quasi-static acoustic emission level from a macro perspective. It is also noticed the occurrence of AE spikes along the pattern, which is due to the start and end of each segment fabrication derived from the step motors drive, but not at the same magnitude and time period.

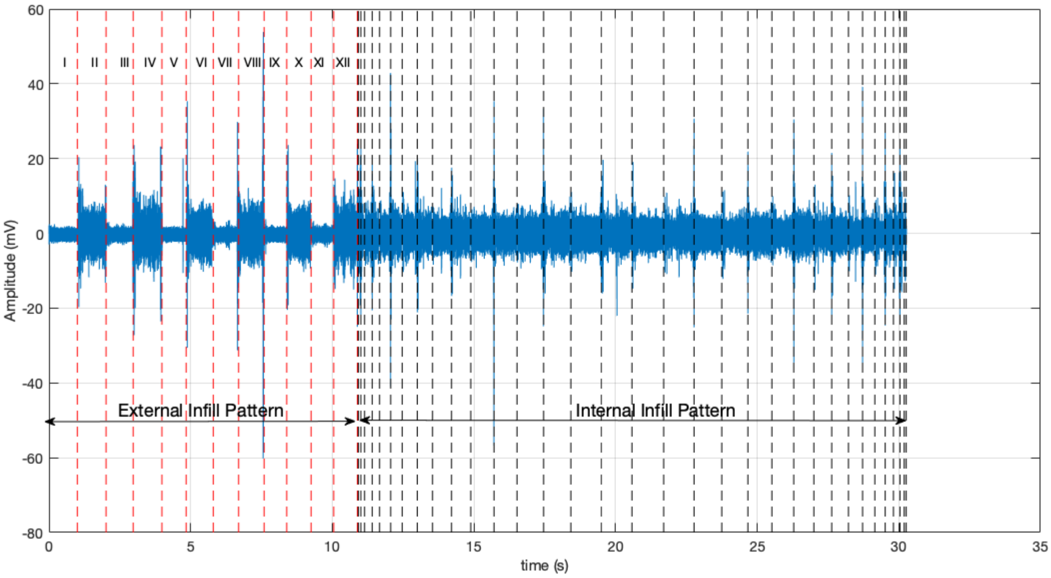

Figure 3. Raw AE signals during the fabrication of the part.

Figure 4 shows the AE RMS signals obtained for both EIP and IIP during the whole fabrication of the part. The vertical dashed lines represent the segments manufactured along the whole printing process. As observed in the raw signals, from a macro analysis, the segments are well defined for the EIP in the transitions between the extruder and table movements, but not for the IIP fabrication during which both extruder and table move simultaneously. However, the segments can be defined approximately when the signals are magnified in this region, as shown in the right upper corner of Figure 4. The amplitude of the acoustic emission for each segment varies for both patterns due to the specificities of these mechanisms of movements, which may be objectives of further study. Finally, the same observations previously presented for the raw AE can be considered to the RMS signals regarding the generation of acoustics during the fabrication process.

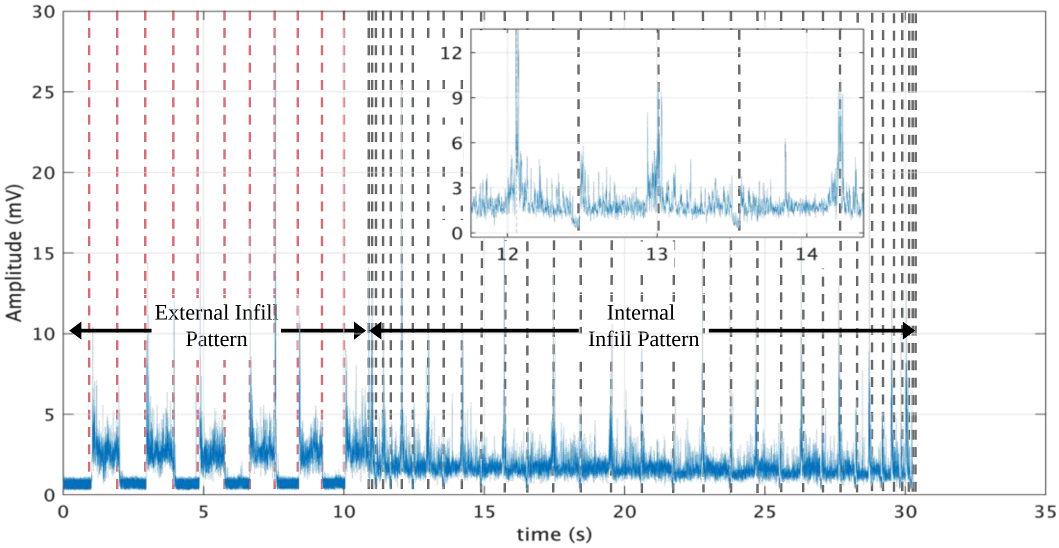

Figure 4. RMS AE signals during the fabrication of the part.

Figure 5 shows the AE mean values for each fabricated pattern and the corresponding standard deviation. It can be seen a nearly constant mean values for each type of line fabricated, which is expected. The differences observed are due to the random AE peaks along the entire process in addition to some imprecision of the method in extracting the lines, which was based on the RMS signal, as described previously. The standard deviation values, however, are very high, which can be explained by the occurrence of AE spikes along the entire process, which mostly are due to the step motors, as observed earlier, as well as to other random signals that need to be further studied.

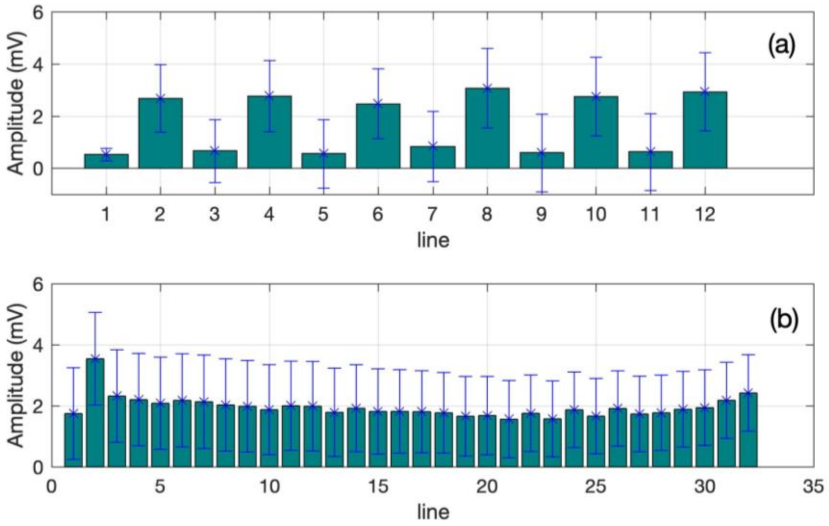

Figure 5. AE RMS mean values: (**a**) EIP; (**b**) IIP.

4. Conclusions

This work has presented the study of AE signal behavior in the time-domain during the fabrication of a single layer part in the FFF process. It can be concluded that the raw acoustic emission signals behave quite differently not just for the two infill patterns, but within the same pattern. It was verified that the main sources of acoustics from the 3D process are the vibration from step motors attached to the printer structures, whose vibration levels depend on the load, as supported by other research studies. It was evident the lighter acoustic emission level occurred for the only-extruder movement, in contrast with the only-table and table-extruder movements. The raw and RMS AE signals contain many spikes along the whole process, but the higher ones were those generally occurring at the end and/or start of a fabrication line. At certain extent, the RMS values have a similar behavior to the raw signal regarding the process noise, in addition to be helpful to finding the start and end times of each fabricated line for both patterns. The mean RMS values have shown a nearly constant but different averages for the only-extruder, only-table and extruder-table movements. The standard deviation values, on the other hand, were very high, as expected, due to the inherent spikes from the noisy process. This work is preliminary and valid for the conditions and printer used.

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