Student-Led Research:

Exploring the Impulse Response of Linear Time-Invariant Systems.

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Abstract

This paper reviews a student-led, extracurricular research project that was a direct out-growth of an in-class research assignment. Within the Signals and Systems course in the Electronics Engineering Technology (EET) program at Pittsburg State University (PSU), the theory of convolution, linear time-invariance, and impulse response are introduced. The PSU-EET program prides itself on hands on application of engineering principles in every class. But providing meaningful applications of convolution and linear time-invariant systems at an introductory level can be difficult. The in-class research assignment was an attempt to demonstrate meaningful application of these two fundamental theories.

The research assignment asked students to (1) model the acoustical response of various spaces using an acoustical impulse response and (2) find an adequate acoustical simulation of an impulse signal.

Fun and applicable experiments that help move the theory from numbers on a paper to the physical world, can engage students by capturing the imagination and help with comprehension of somewhat abstract concepts. The experiments were particularly engaging for three students who conducted additional research based on the course experiments. Pittsburg State's state-of-the-art *Bicknell Family Center for the Arts* has configurable acoustics. The modeling of this acoustical space in different configurations utilizing the impulse response was performed and analyzed by these students. This paper reports on the results of that student-led work.

Background of the Assignment

In the 2010 Midwest Sectional conference of the ASEE, Dr. Perrins presented a paper entitled *Fun with Convolution and Linear Time-Invariant Systems* [1]. In his paper he discussed a fun little experiment he performed with his signal analysis course to solidify the idea of impulse response. At that presentation was a new, first-time faculty member at Pittsburg State who was coincidentally developing / proposing a new undergraduate course in signal analysis. The fortuitous timing of the presentation led to variations of Dr. Perrins experiment being adapted to the new course at Pittsburg State.

In Perrins paper students were tasked with developing a method(s) of generating an acoustical impulse, i.e. popping a balloon or hitting two pieces of wood together. The acoustical impulse was then generated within a well-known acoustical environment, the KU basketball arena. If the impulse method the students devised was a relatively good approximation of an acoustical impulse, then the result was an approximate mathematical model of the arena. Convolving the impulse response with a clean voice signal produced the effect of the clean voice signal sounding as if it was in the basketball arena, giving the clean voice signal a 'stadium' feel. If the generated noise did not approximate an impulse, the resulting convolution was distorted in undesirable ways.

The above scenario only works if 1) the noise generated is a reasonable approximation of an impulse and 2) if the acoustical environment is a linear time-invariant system. Over the years at Pittsburg State similar for-credit course experiments have been performed. In one iteration students have been given a linear time-invariant acoustical environment and was to suggest various methods of impulse generation. This is very much like the Perrins experiment. In another iteration, students were given a method of generating an impulse and were saddled with the task of testing various acoustical environments for linearity. In the fall 2017 semester at Pittsburg State students were tasked with a combination of both variables, the impulse and the system. They tested multiple systems with multiple impulse generation techniques. Each group chose their own impulse generation technique and their own acoustical system to test.

One group of students tested the new *Bicknell Family Center for the Arts* on the Pittsburg State campus. This system was particularly interesting because the Bicknell center utilizes configurable acoustics. Operators can change the position of the theater's soundboards to alter acoustical effects. This idea caught the imagination of the students who were performing the impulse response experiment. They asked the question, '*Is there a measurable difference in the impulse response when the room's acoustics is altered*?' This led to the student driven research.

Impulse Response and Convolution Theory

A mathematical impulse (delta or dirac function) is a theoretical signal used in system theory. An impulse signal has an infinite magnitude at a singular moment in time [2]. The result on an X-Y plane is a signal with a zero value everywhere except at that moment in time that has a width of zero and an infinite magnitude. In the limit, the area of this theoretical signal is unity. Of course this is not a practical or even realistic signal and can thus only be approximated in the real world.

Because the area integral of the impulse equals one, the convolution integral of an impulse with a linear, time-invariant system yields the system. This theory allows one to model a system by injecting an impulse into the system and measuring the result. The measured result is the system. Equation 1 is the impulse integral equation with one signal being an impulse signal. Figure 2 shows a simplified block diagram demonstrating the impulse response of the system. When an impulse is the input the output is the system.

$$Y(t) = \int_{-\infty}^{\infty} h(\tau)\delta(t-\tau)d\tau$$

Equation 1: Convolution Integral using the Delta Function

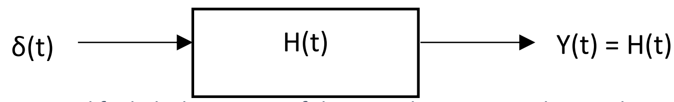

Figure 1: Simplified Block Diagram of the Convolution Integral using the Delta Function

In the real world an impulse signal can only be approximated. The physical impulse response of a space is captured by recording an acoustical impulse approximation generated in the space. The recording captures the actual impulse approximation and the systems response, i.e. reverberations from the space. The reverberations are the response.

A good example of a physical approximation of an impulse is the sound of two hammers being hit together. The reasons for this will be discussed further below. This sound is generated within the acoustical space being tested. The recording of this sound and the reverberations of the space constitutes the mathematical model of the acoustical space.

After recording (1) the impulse response of the space under test and recording (2) the clean voice signal, the two signals can be convolved. The result is the 'clean voice signal' sounds as if that audio is occurring in the acoustical space being tested. For instance, a clean voice recording of a student speaking the words "the answer to life, the universe, and everything is 42" may be spoken in an acoustically clean environment. An impulse response is recorded in an auditorium. After convolving the two recordings, the result is the words "the answer to life, the universe and everything is 42" sound as if they are spoken in the auditorium.

Bicknell Acoustics

One of the most fascinating aspects to the newly constructed Bicknell auditorium at Pittsburg State University is the ability to alter the acoustic response of the theater based on the positioning of nine pair of dampening panels throughout the auditorium. Each set of panels can be retracted and extended to alter the acoustical damping of a room (Need a reference). The nine pair can be configured in many permutations in order to achieve the optimal sound response of the room. The experiment performed was not exhaustive. The experiment does not test all possible position combinations. Instead, five fundamental positions are tested in this research. Those positions include when theater is (1) 0% damped, (2) 25% damped, (3) 50% damped, (4) 75% damped and (5) 100% damped. To achieve each of these settings the panels were manipulated by the staff at the Bicknell Center to preset values.

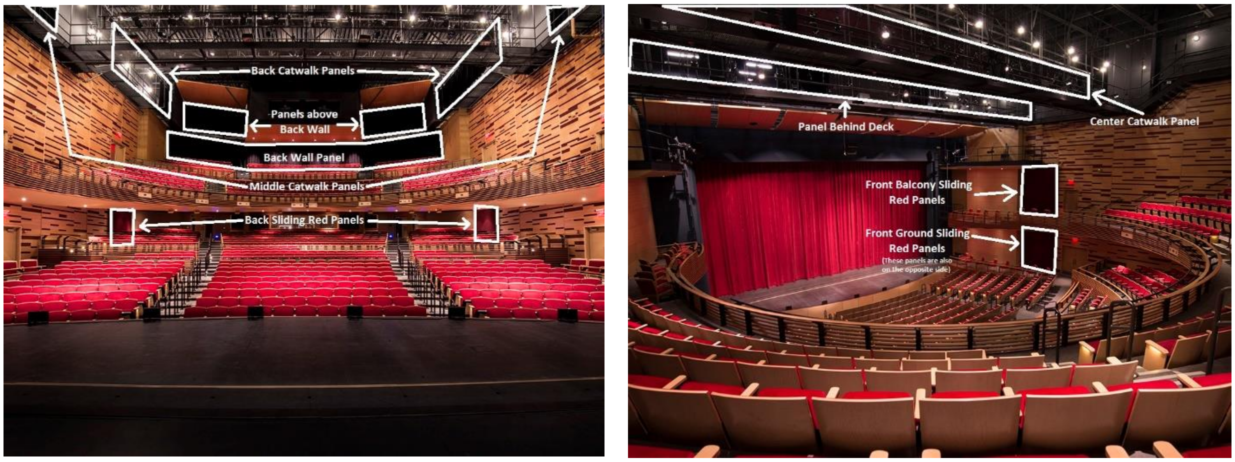

Figure 2 – Inside the Bicknell Center. Each damping panel is highlighted.

Methodology

The in-class research assignment simply asked for three different acoustical spaces to be tested for linearity. When the Bicknell was selected as one of these spaces, altering the dampening panels was not a consideration. A small set of students determined to continue the investigation by returning to the Bicknell Center to collect more data at various damping rates. With the help of willing Bicknell Center staff, the response of the Bicknell auditorium was recorded with the acoustic panels in different stages.

Testing of several methods of generating an impulse approximations was performed. Comparison of the impulses was done aurally. A good impulse had the shortest burst of sound followed by as little other noise as possible. The results demonstrated that two hammers being struck together was the best auditory impulse approximation from the various methods attempted. The graphs in Figure 3 visually hints at what was confirmed aurally. The impulse of the two hammers has almost no noise after the impulse where the wooden blocks striking together has trailing reverberations. This makes the hammers closer to the ideal impulse that is used in the mathematical model.

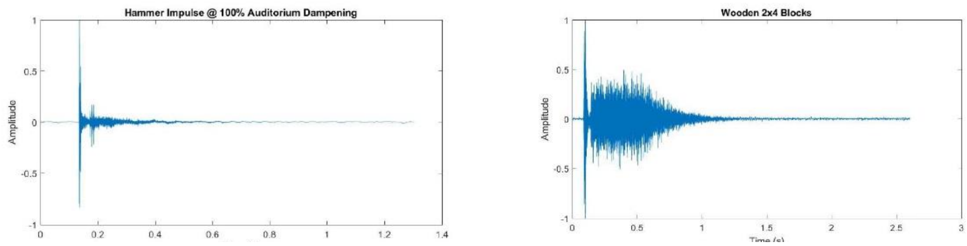

Figure 3 – (Left) Impulse of two hammers being struck together, (right) Impulse of wooden blocks being struck together.

A recording of a person speaking was captured in a recording studio with extremely good sound absorption properties. All audio recorded for this project was recorded by a high quality condenser mic supplied by the Bicknell center staff. Convolution of the two signals was performed in MATLAB.

This course was a first exposure to LTI systems, impulse response and convolution. Therefore the method used to determine linearity is not a precise scientific measure, rather it is an empirical aural method. Assuming a good impulse signal, a space is more linear if the convolved audio sounds like it was spoken in that space. The room is less linear if the convolved audio does not sound like the room it was spoken in. A non-linear space, such as a space that generates an echo, clearly manifests itself as non-linear when listening to the convolved audio. However, when a system is generally linear with a minor contribution of non-linear features, then the aural testing becomes more subjective. For comparison purposes, the clean audio recording was also re-recorded at center stage. Thus what the sound actually sounds like at center stage could be compared with the convolved sound.

Experiment

The position of the panels are manipulated to allow for 5 panel configurations for our experiment. These variables consist of 100% damped, 75% damped, 50% damped, 25% damped, and 0% damped. The determination of which panels would equate to which dampening factor was determined by professionals at the Bicknell Center. At 100% the curtains cover all of the panels providing total damping of the auditorium. At 75% the curtains are removed from the panels behind the deck and from the middle catwalk panels. At 50% the curtains are removed from the panels above the back wall, on the back catwalk panels, and the center catwalk panel. At 25% the curtains are removed from the back wall panel. At 0% the sliding red panels in the front on the ground and balcony as well as the back sliding red panel are stored away into the walls.

The impulse was generated at center stage in the auditorium. The microphone is placed close to the impulse in order to capture the original sound of the impulse plus the sound of the impulse response. The result of this microphone location is the mathematical model is the mathematical model of the auditorium at center stage.

Results

The following five graphs represent the time-domain impulse response of the Bicknell auditorium in five different damping configurations. Those five configurations were referred to by the Bicknell operations staff as 0%, 25%, 50%, 75%, 100% damped. The precise technical meaning of percent damped is unclear. Here the term is used as labels for each auditory setting.

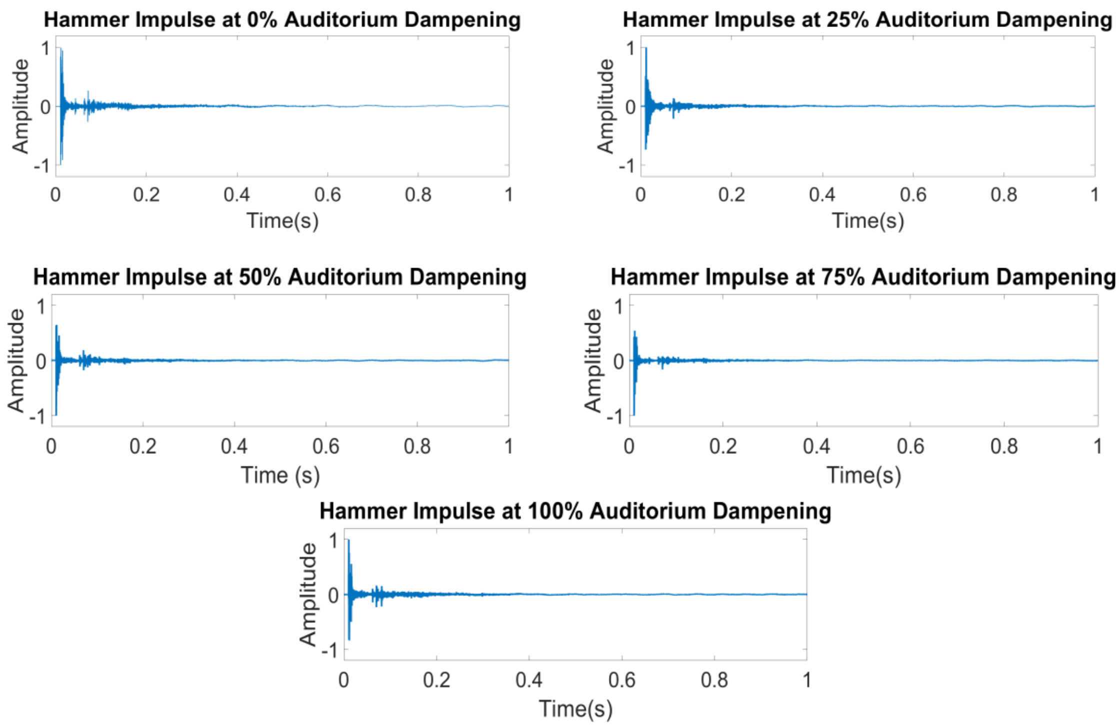

Figure 4 –Impulse response of Bicknell Center in five different auditory configurations

Visual inspection of these five graphs do not present a drastic difference. Comparison of any of the five responses above to the same impulse injected into a complete different auditory system reveals a stark difference. The graph below represents the auditory response of an impulse in a PSU classroom.

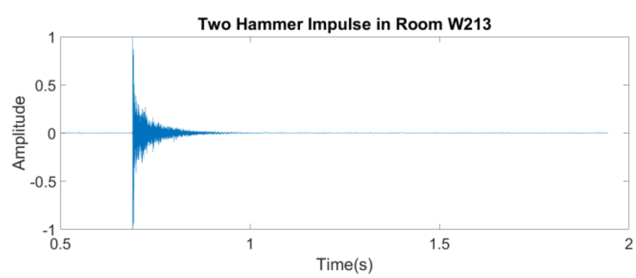

Figure 5 – Same impulse performed in a classroom.

The five recordings in the Bicknell Center are distinct from the classroom response. This is anticipated as the Bicknell system changes are not quite as drastic as changing spaces altogether. After recording the impulse response of each of the five systems, a clean audio sound wave was convolved with each impulse.

The clean audio signal, recorded in a sound studio is shown in Figure 7 below.

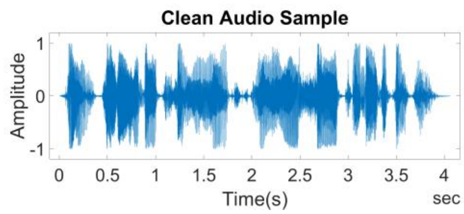

Figure 6 – Clean audio signal

The following five signals are the clean audio signals convolved with the impulse approximation signal.

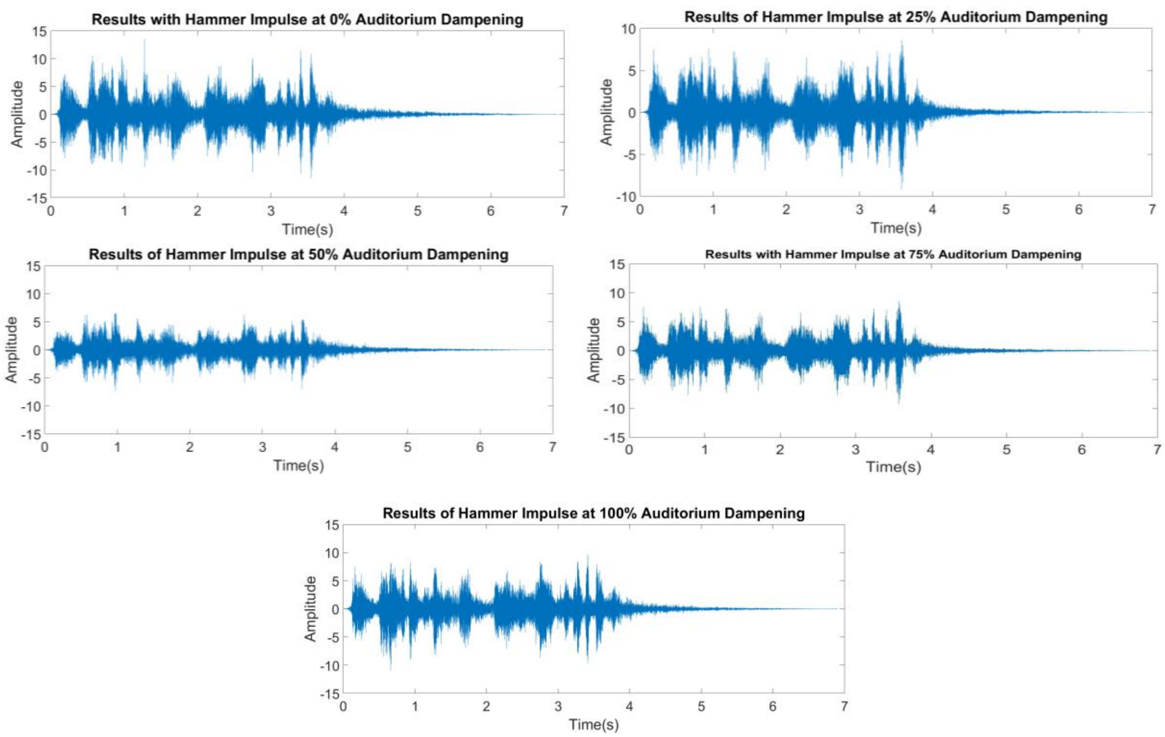

Figure 7 – Impulse response of each configuration convolved with the clean audio signal.

Analysis

By inspection, it is difficult to see a distinction in these five signals. An aural comparison was more distinctive. The sound dampening panels reduce the magnitude and temporal length of reverberations. As the damping increased from 0% damped to the 100% damped setting, the noise from reverberations decreased. A comparison between only the two most extreme settings illustrates the change most clearly since the difference between the two responses is greatest. The 100% damped setting had noticeably less distortion and less echo than the room that had no dampening. The final convolved audio of the room that had no damping was hollower sounding than the room that had dampening.

Each convolved audio sample was compared to the actual sound of someone speaking from the stage in the Bicknell Center at the different damped levels. The signals matched relatively closely. None of the signals contained noise that was characteristic of non-linear spaces. One may conclude that at each of the damping ratios, the Bicknell Center was acoustically linear. At the same time, there was variation in the signals enough to demonstrate that the acoustics do vary as the dampening panel configuration is changed.

Educational Outcomes

The purpose of the in-class experiment was to take fairly abstract concepts and bring those concepts to life, capturing the imagination of students. From this perspective the implementation of the in class experiment was successful. Students willingly took on additional work to continue a class experiment for the purpose of doing research. This was only one data point, but it is apparent in this data point that objectives were met.

Moving students out of the classroom has many advantages. Hands on investigations with open ended results can stimulate active learners [3]. Group projects prepare students for real-world tasks [4], they are more engaging for students, and they encourage collaborative learning. Further, any engineering principle that can be put into action, seen, touched, or anything that is different from the normal humdrum day of a student, are those things that have the best chance of reaching a student. Orchestrating large class projects injects significant time restraint on instructors, however anything that breaks routine can increase retention of ideas and be motivating. Not all students respond positively to breaks in routine. Anecdotal evidence indicates that even those students will recall the experiment and retain principles learned in those experiments much longer than standard lectures.

Experimental Conclusions

The Bicknell center's acoustic panels change the response of the room. The aural response difference was distinctly noticeable between the 0% damped setting and the 100% damped setting. The results indicate the Bicknell Center is an acoustically linear system. Non-linear acoustic components could be heard when panels were placed at 0% damped. Non-linear components were negligible when compared to other non-linear acoustic spaces. The concepts of linearity, convolution and impulse response was vivified by this project.

Educational Conclusions

Though not much can be concluded from this very small sample size, the experience does bring to light some interesting questions about the pedagogy of this type of educational experience. For instance; does out-of-class experiences contribute to (1) retention of principles, (2) comprehension of principles, (3) motivation, or (4) development of lifelong learning desires? If the answer to these questions are 'yes', the real dilemma for educators is developing out of class experiences that are meaningful and motivating. My personal experience has informed me that when students view assignments as meaningful and motivating, they will invest more time and energy, even when the assignment is hard, and they will like it.

References

[1] E. Perrins, "Fun with Convolution and Linear Time-Invariant Systems," in *Proceedings of the Midwest Section of the ASEE*, Lawerence, 2010.

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[4] L. F. S. Johns-Boast, "Providing Students with 'Real-World' Experiences Through University Group Projects," in *Proceedings of the 2009 Annual Conference for the Australasian Association for Engineering Education*, University of Adelaide, 2009.