Hot Swappable Guitar Effects Pedal Auditioning System

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Abstract

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Chapter 1

Introduction

The sound of an electric guitar is a complex combination of processes. Unlike a purely acoustic instrument, timbre is not purely a result of the vibration of the wood and strings. The pickups, amplifier, and speaker are all in a sense part of the instrument. In addition to these standard components, many electric guitarists use one or more effect pedals to augment or alter their sound. First developed in the 1960s, there are now thousands of pedals available for guitarists to use.

1.1 Current Guitar Effects Pedal Auditioning Methods

The wide variety of options for guitarists to choose from means that it can be difficult to decide which product to purchase. Though in an age of Internet shopping there are many guitar related products available for purchase on-line, most players want to test potential purchases in person before buying them. Subtle differences in sound and feel make this live testing paramount. As such, brick-and-mortar music stores such as Guitar Center still have a place in the industry.

1.1.1 Permanent Display Board

There are two existing methods for testing effects pedals at brick-and-mortar retail stores such as Guitar Center. The first one that many guitarists experience is the permanent display board. While most of the in-stock effects pedals at retailers like Guitar Center are stored in a general display case for customers to peruse, some larger companies have dedicated, integrated display boards to showcase their products. For example, Figure 1.1 shows one such display, containing products from Boss, one of the most popular companies in the industry. As can be seen, the pedals are permanently attached to the display board, and are connected in series, with power available to all effects at once. The last pedal in series remains connected to a dedicated guitar amp, so customers must only plug a guitar into the input of the display unit to begin auditioning. This facilitates easy switching between any of the pedals that are included in the display. Much like they would when using the effects in their own pedalboard after purchase, the user can select which effects are engaged simply by activating the foot switch on each pedal. This makes it quick and easy to switch between different effects.

However, this system has some limitations. The first is that it is generally limits a customer to testing pedals from a single manufacturer at any time. This is especially important if they are attempting to decide between several similar options from competing companies. The second issue is that the order of connection of the effects is fixed. In general, changing the connection topology of effects can result in radical differences in the output, which can affect the perceived quality of a pedals sound. For example, consider the different possible methods of connecting a distortion and delay pedal. As the distortion effect is typically the result of signal gain and clipping, it is inherently non-linear, which helps explain the differences in sound for different connections. If the distortion is connected in series before the delay pedal, the sound might be the main distorted guitar sound with some echoes of this distorted sound. If the guitar is first connected to the delay instead, the echoes will be all the same volume as the gain and clipping of the distortion will even out the amplitude. In theory, it is also possible to connect the two pedals in parallel, which would result in the main distorted guitar sound and echoes of the "clean", unaffected guitar. A feedback connection where the distortion pedal is connected in a feedback loop of the delay might also produce interesting results. As can be seen even with this simple example involving only two effects, there are a multitude of possible connection topologies available to guitarists if they are not limited by the fixed connections of display boards.

The last major issue stems from the bypass method used by many of these units. Many guitar pedals, include all of the products offered by Boss, include a buffer that is active when the main "effect" is bypassed. This is useful for performing guitarists who often use cables totaling up to fifty feet in length. The capacitive loading from the coaxial instrument cables can result in high frequency loss, as guitar pickups can have DC output resistance on the order of $10k\Omega$. A high input impedance and low output impedance buffer located in a pedal can help reduce the effects of this typically undesirable high frequency attenuation. However, because these display boards can contain thirty or more effects, there can be issues with signal degradation when so many buffers are connected in series.

In some cases, these buffers can have an additional consequence that can be undesirable for certain types of pedals with low input impedances. Effects like the "Fuzz Face", made famous for its use by Jimi Hendrix, can have an input impedance on the order of $10k\Omega$, which is similar to the guitar's output impedance. This means that there can be interactions between the two circuit blocks, which can be subject to change based on the position of the guitar's on-board controls as well. Though in typical engineering applications interactions between circuit blocks is undesirable, many guitarists prize this "interactiveness" as a benefit. Placing a buffer between the output of the guitar and the input of the pedal disrupts these interactions.

Figure 1.1: A permanent display board typical to those found at retail stores such as Guitar Center. This particular example is from Boss, one of largest guitar pedal manufacturers, and one of the most ubiquitous companies to use these display boards.

1.1.2 Free Connection Method

The other common method guitarists use to test effects pedals will be referred to as a "free connection" method. If a customer wishes to compare two pedals, they must request an employee to bring the particular units to a demo table, as seen in Figure 1.2. To perform an A-B test, the customer must turn the amplifier output off to prevent pops before disconnected the current pedal being tested and replacing it with the other, if they wish to avoid issues with buffers mentioned above. This time required for swapping the pedals limits the customer's ability to accurately judge the relative qualities of the units under test. This cost can result in several negative consequences. First, because of the reduction in accuracy of the A-B test, the guitarist may not be able to make a well-informed decision as to which effect best suits them, which could result in them either purchasing an inferior product, or in them deciding not to purchase any product at all. Second, the known difficulties of testing effects pedals in this way may deter potential customers from even bothering at all. This would either limit people from making ”impulsive” purchases or encourage people to buy both of the products they are interested in, test them at home, and return the one they did not prefer. The latter is inefficient for retail stores to deal with many returns and refunds. Despite these drawbacks, this method is preferred if pedals from multiple manufacturers are being compared or if the routing configurations being tested are more complex (i.e. the user wants to test two pedals in different orders).

Figure 1.2: A typical ”test bench” demo board found at Guitar Center, Boston MA. The surface is carpeted to avoid scratching the pedals. Sitting on the surface is a portable type of display board. Several cables and power supplies can be seen. The amplifier used for testing is located below the table on which the demo board rests.

1.2 Problem Statement

The benefits and drawbacks of the two guitar effects pedal auditioning methods are summarized in Table 1.1. Clearly, neither method is ideal, and the issues resulting from each’s drawbacks are a detriment to both potential customers and to retailers. Therefore, guitarists need an improved process to audition guitar pedals to facilitate more expedient and accurate purchasing decisions.

Table 1.1: Summary of Current Guitar Effects Pedal Auditioning Methods.
A good solution system would combine the benefits of both methods.

Method	Attributes			
	Ease of Use		Flexibility	
Display Board	✓	Just activate footswitch to engage effects	✗	Single manufacturer; fixed routing order; potential signal degradation unavoidable
Free Connection	✗	Requires plugging and unplugging signal and power; generally slow	✓	Any manufacturer; many connection topologies possible; power supply can be selected

1.3 Design Requirements

In practice, a solution should combine the best attributes of the two current methods. This involves fulfilling two broad categories of requirements. The requirements of the first category ensure that the solution shows a functional improvement over the previous methods; it should solve the problem described in the problem statement. The most pertinent requirement for this is a reduction in the ”swap time”, or the time required to switch between two pedals in an A-B test. This fundamental situation is important to any sort of auditioning. To make it worth the effort of going through this project and for retail stores to implement, a solution should offer a major improvement in swap time. An order of magnitude improvement seems like a reach goal, but an 80% improvement in swap time over the free connection method is reasonable.

In order for the solution to be effective, it must be usable with a majority of pedals available at typical retail locations. An 80% market coverage is reasonable because a majority of retailer stock contains pedals by just a handful of brands. There is a trade-off between universal compatibility versus form and function, so designing for every possible pedal should not be a priority, though a solution design should not preclude an eventual expansion of compatibility.

For a retail store to use a solution, the cost to implement it in the store should not be obtrusive. As the solution developed in this project is not intended to be production ready, the material cost rather than the final cost is specified. A initial cost of $200 should cover the main part of the system, and the incremental cost to make any additional pedals compatible with the system should be no more than \$20 per pedal. The latter cost is a more important point, because many retail stores may stock hundreds of guitar pedals, so the individual cost must

Finally, the solution system should be as intuitive as possible. This is not easy to quantify, though a simple metric might be the number of words required to give useful working knowledge of the system in a user guide. However, this seems fairly artificial, as an instruction manual could be continually optimized to reduce word count ad nauseam, so performing an actual verification measurement on this requirement would be rather contrived. Instead, this requirement should be kept in mind during the design phase as an important consideration.

The second set of requirements deals with the ability of the system to be an unbiased method of comparison, adding no coloration to the sound. These signal quality properties include signal-to-noise ratio (SNR) and frequency response. The signal-to-noise ratio of the electric guitar itself, by virtue of its simple passive magnetic pickups, can be very high. Preliminary measurements suggested an SNR around $90dB$. Higher values in a controlled environment are likely. Noise in guitar audio is particularly important, as guitar amplifiers apply a high level of compression and amplification which can significantly increase the noise floor at the speaker. Particular care must be taken to reduce noise earlier in the signal chain to prevent its amplification. Most guitar effects are specified with SNR ranging from $80 - 120dB$, but some of these manufacturer-supplied specifications may be over-inflated, and in most cases are A-weighted, deemphasizing certain parts of the frequency spectrum. Thus, a $90dB$ SNR is a good baseline requirement.

As in any audio system, the solution's frequency response should be flat across the audio range. Because very subtle differences in the timbre and frequency content resulting from the use of different pedals is vitally important, a $0.1dBu$[1] flatness is required across the audio frequency range $20Hz$ - $20kHz$. Performance down to very low frequencies or even DC would be useful for some subharmonic effects and synthesizer pedals, so this would be a plus.

In addition to these signal quality considerations that are important during the actual listening process, the system should also have a short switching time so the user perceives no delay when swapping a pedal in or out of the system. Because it should be easily achievable with most switching method that might be used while being short enough to have no perceived discontinuities, the system should have a switching time of no longer than $20ms$. Note that this is the time required by the system to switch signals and is a

[1]Note that dBu is a standard audio unit compared to a reference voltage resulting from a 600Ω load dissipating $1mW$ of power. $0dBu = 0.775V_{rms}$.

Table 1.2: Summary of Design Requirements.

Metric	Target Value	Notes
Swap Time	80% Reduction	
Compatibility	80%	
System cost	\$200	Materials cost for the initial system
Incremental cost	\$20	Materials cost for each additional pedal that is made compatible with the system.
SNR	$90dBu$	
Frequency Response	$0.1dBu$ flat over $20Hz - 20kHz$	
Switching Time	$20ms$	
Transient	$0.5dBu$	Transient added by system during switching

separate requirement than the swapping time described above.

Finally, to ensure the safety of the equipment following the solution system, switching transients should be limited when switching a pedal in or out of the system. The transients added by the system should be no larger than $0.5dBu$.

These requirements are summarized in Table 1.2

Chapter 2

System Design

2.1 System Overview

Though it may appear trivial at first, the broad scope of the design space of this project meant making difficult design decisions where there was often no clear answer. The first major decision was determining the approach used to reduce the swapping time. Inspired by the battery connectors in some wearable devices, a hot swapping connector design was chosen. Hot swapping refers to the ability to connect or disconnect a peripheral, in this case a guitar pedal, without needing to perform any special preparatory actions such as turning off the power. This type of design unites a physical action of inserting or removing a pedal into a system with the electrical switching actions required to actually perform the hot swapping.

With this decision made, the high level design of the hot swapping device was considered. To be able to insert a pedal into the signal chain at any time meant that the solution required a main signal control device, which acts as a "meta pedal", connected between the guitar and an amplifier. When the hot swapping device is not activated, the guitar signal is connected directly to the amplifier. When the hot swapping action occurs, the signal is routed through the hot swapping connector to the pedal and back, allowing the pedal to be inserted into the signal chain between the guitar and amplifier.

This required standardizing the interface between the guitar pedal and the device. Data collected during a site visit to a Guitar Center retail location demonstrated the plethora of effects pedals available at a standard brick-and-mortar store. These 150 pedals represent a good mix of products, from mass market production units such as the Boss DS-1 to high quality and expensive effects like Eventide's H9. While the major manufacturers like Boss, MXR, and Electro Harmonix have narrowed their form factors down to a handful of types each, there is no standardization across producers on features important for this project, including the dimensions of the enclosure, the location and orientation of the signal and power jacks, the location of the screws used to hold the pedal's bottom plates. Though most products use the de facto standard 9 VDC, center negative power supply connected with a 2.1 mm plug, this too has variations in some cases. All of these variations complicate standardizing a form that can easily be hot swapped. A universal adapter was designed to connect the pedal to the hot swapping device.

On a high level, the design process focused on ease of use and intuition for the user over any other considerations where possible, which explains the preference for this tactile and tangible hot swapping method over a programmable switching device, for instance. The push for simplicity has led to some increases in design complexity, including the need to automatically detect when a hot swapping event occurs rather than include a separate user controlled switch.

In order for a user to be able to test multiple effects, multiple hot swapping devices were included in the device. An internal signal routing system was also designed to facilitate testing pedals in different routing configurations including series, parallel, feedback, and various combinations of these. Finally, a user interface was designed to control this internal signal routing.

Because of the repetition present in the device, it was designed as a modular system to simplify design, fabrication, and evaluation. Figures 2.1 and 2.2 show a hierarchical block diagram of the system. The system level diagram shows three modules were used for the full implementation of the system, with only audio passing between them. The same $24VDC$ power input was passed to each module. The module level diagram shows the major constituent parts of each module. The design and function of each of these will be discussed in the remainder of this chapter.

2.2 Design Decisions

2.2.1 Universal Adapter

Because of the large variety of guitar pedal shapes, they are not by themselves suitable for hot swapping in and out of a fixed receiving unit. A universal adapter was designed to interface between the pedal's I/O and the hot swapping connector. The required attributes for this adapter include a way to mechanically mount a pedal, a way to connect to the pedal's I/O, and a way to connect to the hot swapping connector. The last requirement means that there must be exposed electrodes with which the corresponding electrodes on the main device can make electrical connection. It also includes a method to physically align these electrodes when the hot swap device is active. None of these requirement suggest a

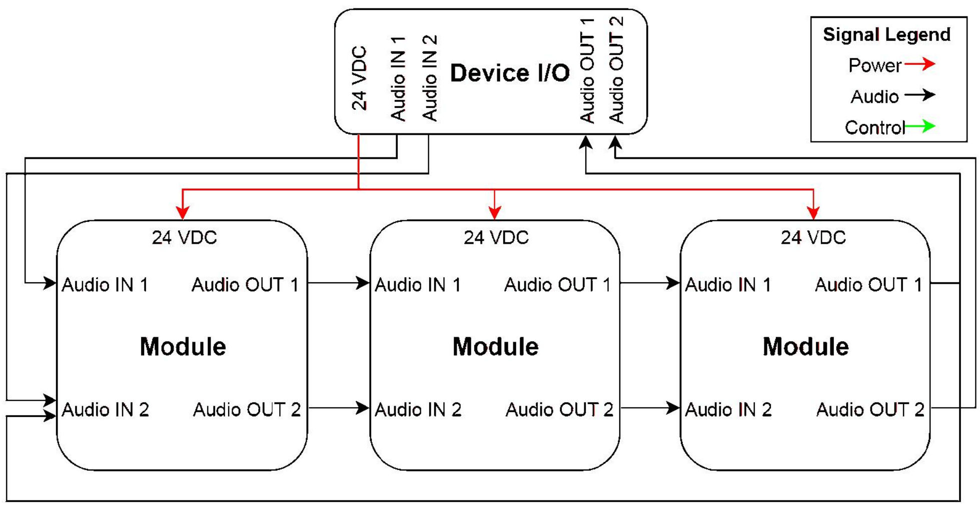


Figure 2.1: System level of hierarchical block diagram. This shows the modular design of the device. The legend in the upper right shows that power is indicated in red, audio signal in black, and control signals in green, with the direction of the arrow indicating data direction. Note that no control signals pass between the modules, making design and debugging simple. The signal and power I/O for the device are passed on to the modules.

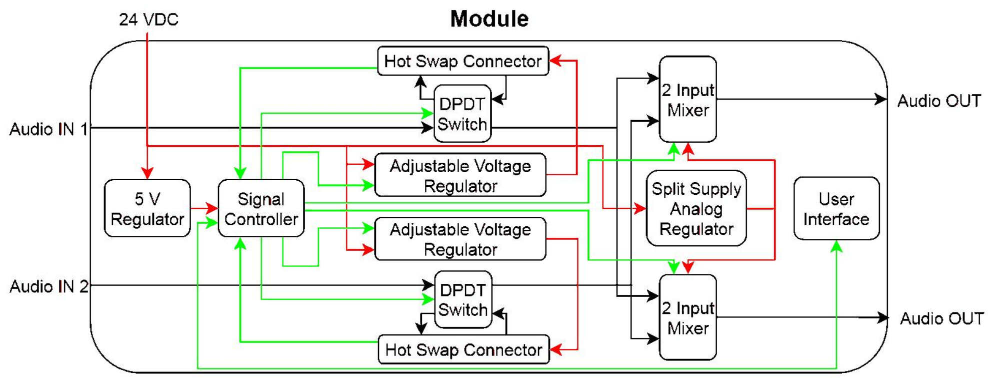


Figure 2.2: Module level block diagram showing the contents of each module. As in Figure 2.1, power is indicated in red, audio signal in black, and control signals in green, with the direction of the arrow indicating data direction. In principle, each module contains a pair of hot swap devices consisting of the hot swap connector, DPDT switching element, and adjustable voltage regulator. The module also contains an internal signal routing mechanism consisting of two mixers and a user interface, as well as all necessary voltage regulators required to step down the 24V input for all these circuits.

need for much vertical height, so this universal adapter will in general come in the form a base plate on which the pedal sits. Because of this, ”plate” is used to refer to this universal adapter throughout the rest of this document.

Pedal-Plate Mounting

The thin and flat nature of the universal adapter plate allows the plate itself to be used as part of fastening the pedal. Holes and slots cut into the plate which allow screws to pass open up several options for mounting a pedal. Because of its simplicity, the most attractive option was to reuse the screws that hold in the pedal's bottom cover. As most pedal enclosures have bottom covers held on by four screws, one in each corner, reusing two screws in opposite corners to pass through the plate allows the cover to remain in place while still resulting in a good mechanical connection between the pedal and the plate. However, because a non-trivial number of effects pedal enclosures have fewer bottom plate screws, or none at all, this method is not completely universal.

To accommodate pedals that do not have the common four-screw bottom plate, a clamping mechanism can be used to modify the method described above. Instead of reusing pedal's bottom plate screws, a clamp in the shape of a corner bracket is placed over the top corner of the pedal, and a screw is again passed through the plate used to tighten the corner clamp down, securing the pedal along with it. This solution allows the same type of holes and slots used with the direct bottom cover screw method. The clamp should be padded to prevent damage to the product. Although this augmentation to the bottom cover screw method would help to increase compatibility, it was not explored further due to time constraints.

The advantage of both of these methods is that they are easily reversible and have no lasting effects on the appearance or function of the product. However, if neither of the above attachment methods was adequate, velcro could also be used to attach the pedal to the plate, as is common with permanent pedalboard setups. However, this can leave a residue on the product so it is less desirable.

INSERT IMAGE OF CORNER BRACKET clamp

Plate Size

The position and dimension of the slots and holes required for the through-screw methods of mechanical attachment mentioned above must be positioned to allow alignment with the pedal's bottom cover screw holes. Because this varies with the exact geometry of the enclosure, these holes should allow for adjustment. Slots were chosen over holes as the primary mating location because of their allowance for adjustment along an axis. To determine the exact shape of the slots, measurements of the physical dimensions of pedals at Guitar Center were taken, to determine a guideline to estimate the relative position of the bottom plate screw holes compared to the outer dimensions of the enclosure. Based on the measurements taken, the distance between screws in any direction is typically 90% to 95% of the outer length of the enclosure in that dimension. Using this, the physical outer dimensions of all of the pedals cataloged at Guitar Center were recorded from each pedal's user manual.

Because only two screws located on opposite corners of the pedal are used to attach the pedal to the plate, a line can always be draw through both of them[1]. Therefore, when designing the mounting slots on the plate it is sufficient only to consider the length of this line segment connecting the two screw locations. Variations in the aspect ratio of the enclosure (width to height) can be dealt with via small rotations. The data collected from Guitar Center stock was used to actually design the minimum and maximum screw-hole-distances

[1] This is very trivial

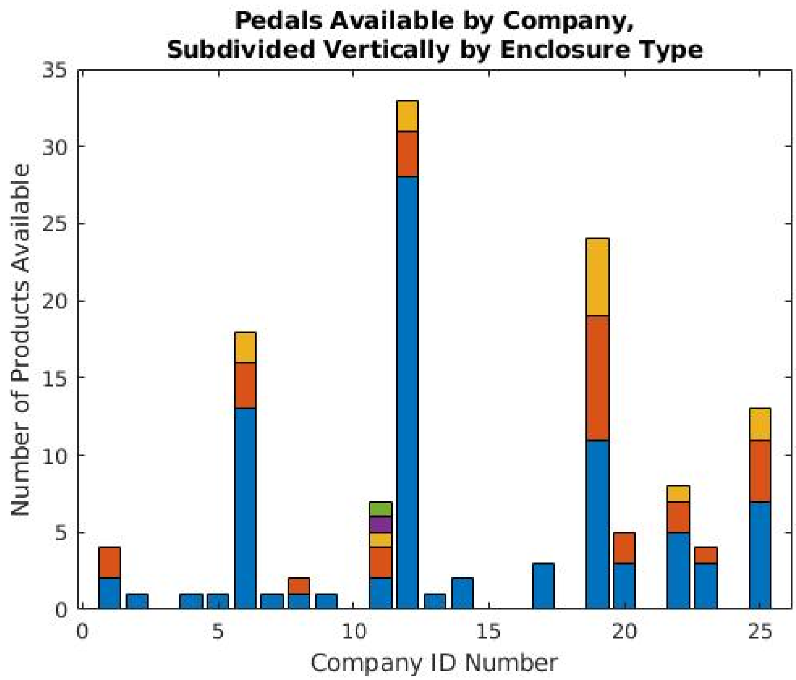


Figure 2.3: Number of guitar pedals available by manufacturer ID. The bars are divided vertically by the type of enclosure used, with the most popular enclosures on the bottom.

that must be covered.

First, the data was broken down by company, and each company was assigned a numerical ID. The number of pedals available from each manufacturer was counted. Then the data was further broken down by pedal enclosure category. Generally, each manufacturer will design many of their products to fit in the same enclosure, which keeps their procurement and design process simpler. This allows the pedals to be grouped by enclosure type, meaning that all pedals offered with the same enclosure will have the same external dimensions and be mechanically compatible with the hot swapping device if any one of them is compatible. Each enclosure type was also given an ID number, and was labeled with the company who uses it and the number of products being offered by that company using this enclosure type. This data was plotted using a stacked bar graph as seen in Figure 2.3, with the company ID numbers listed in Table 2.1. Note for instance that Company 12 (Boss) offers more than thirty pedals, and the vast majority of these use the same variety use the same type of enclosure, meaning that compatibility with this type of enclosure is a greater priority than a lesser used one, such as the type used by Company 9 (ProCo). Note also that the plot only shows effects with their physical dimensions listed in the manual, which explains why J Rockett Audio, which had two products, has no bar on the graph.

Company Name	Company ID	Number of Products Available
Seymour Duncan	1	4
BBE	2	1
J Rockett Audio	3	2
Tech 21	4	2
Ampeg	5	2
MXR	6	18
Korg	7	1
Fulltone	8	6
ProCo	9	1
Danelectro	10	3
Digitech	11	7
Boss	12	33
Eventide	13	1
Way Huge	14	2
Egnater	15	1
Line6	16	1
Fender	17	3
Voodoo Lab	18	1
EHX	19	26
Ibanez	20	5
Maxon	21	1
EarthQuaker	22	8
JHS	23	4
Keeley	24	5
TC Electronic	25	13

Table 2.1: List of guitar effects manufacturers and their associated ID numbers.

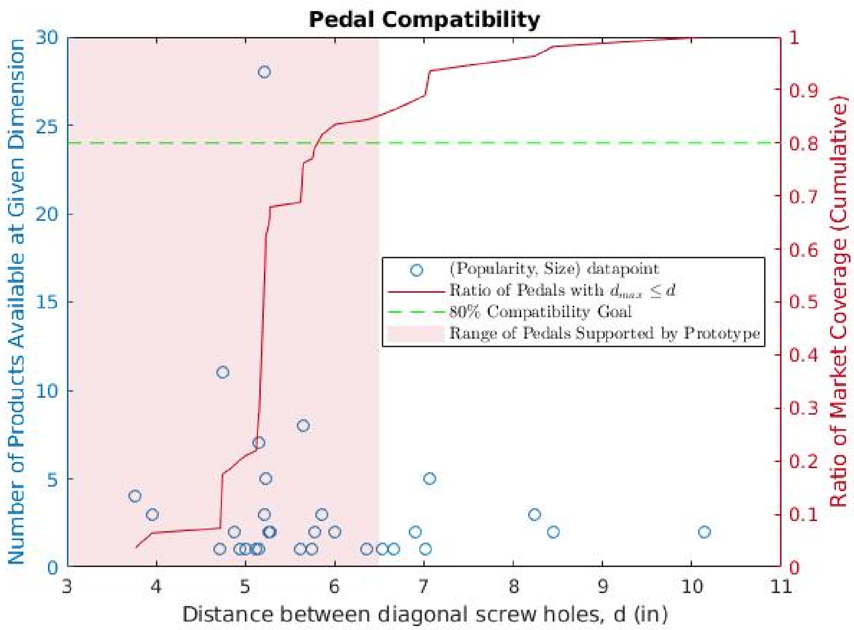


Figure 2.4: Percent of pedals available at a typical retail store that are compatible with plate with diagonal distance d. Because most manufacturers reuse their enclosures for multiple products, it was possible to plot the number of products available in the same enclosure with the diagonal screw distance for that enclosure. A cumulative ratio of the number of pedals available with this dimension or less was superimposed over these data points. Because supporting arbitrarily small pedals is not difficult with the design (one long slot would do the job), the plot was used to determine the maximum size slots required to meet the compatibility requirement. The final design supports a diagonal distance of about 6.5". The area of the plot less than this dimension was shaded to indicate the pedals supported by the design. Because the edge of this shaded region intersects the cumulative graph above the green horizontal compatibility goal reference line, this indicates that the design meets this requirement.

Plate Material

2.2.2 Hot Swapping Device

Electrical Connection Mechanism

Pedal Power Selection

Hot Swap Event Detection

Hot Swap Event Actuation

2.2.3 Analog Signal Routing

Routing Architecture

Analog Voltage Supply

2.2.4 User Interface

Chapter 3

System Implementation

3.1 Circuit Board Layouts

3.1.1 Circuit Board Hierarchy

3.1.2 Component Placement Considerations

3.1.3 Routing Considerations

3.2 Circuit Board Assembly

3.3 Mechanical Assembly

Chapter 4

System Evaluation

4.1 Functional Improvements

The first main category of system evaluation measurements are related to determining if this solution was successful in solving the problem: did it actually allow guitarists to more easily and quickly test out guitar effects pedals?

4.1.1 Swap Time

Experiment Description

The most important measurement related to this is comparing the time required for users to swap between pedals. This experiment used to measure this difference was designed to simulate the expected operating conditions of the system. In this case, each participant conducted four tasks, and the time required to complete each of these tasks was recorded. For each task, the user began wearing a guitar with its output connected through a single guitar pedal. They were instructed to safely remove this guitar pedal from the signal chain, and set it down in a defined location. Then they were instructed to touch a second location before re-inserted the pedal back into the signal chain.

The first three tasks were controls, each conducted with a different standard guitar effects pedal. These test pedals were chosen to represent some of the breadth of products available on the market (see Table 4.1 for details). The guitar pedal was connected in the standard way, with an instrument cable connected from the output of the guitar to the input of the pedal. The output of the pedal was connected to the input of a guitar amplifier. The pedal was powered with a standard $9VDC$ wall wart adapter. To begin, the participant started with their hands on the guitar. The pedal was set on a table of standard height to mimic the environment of testing pedals in a guitar store, instead of on the floor. After a

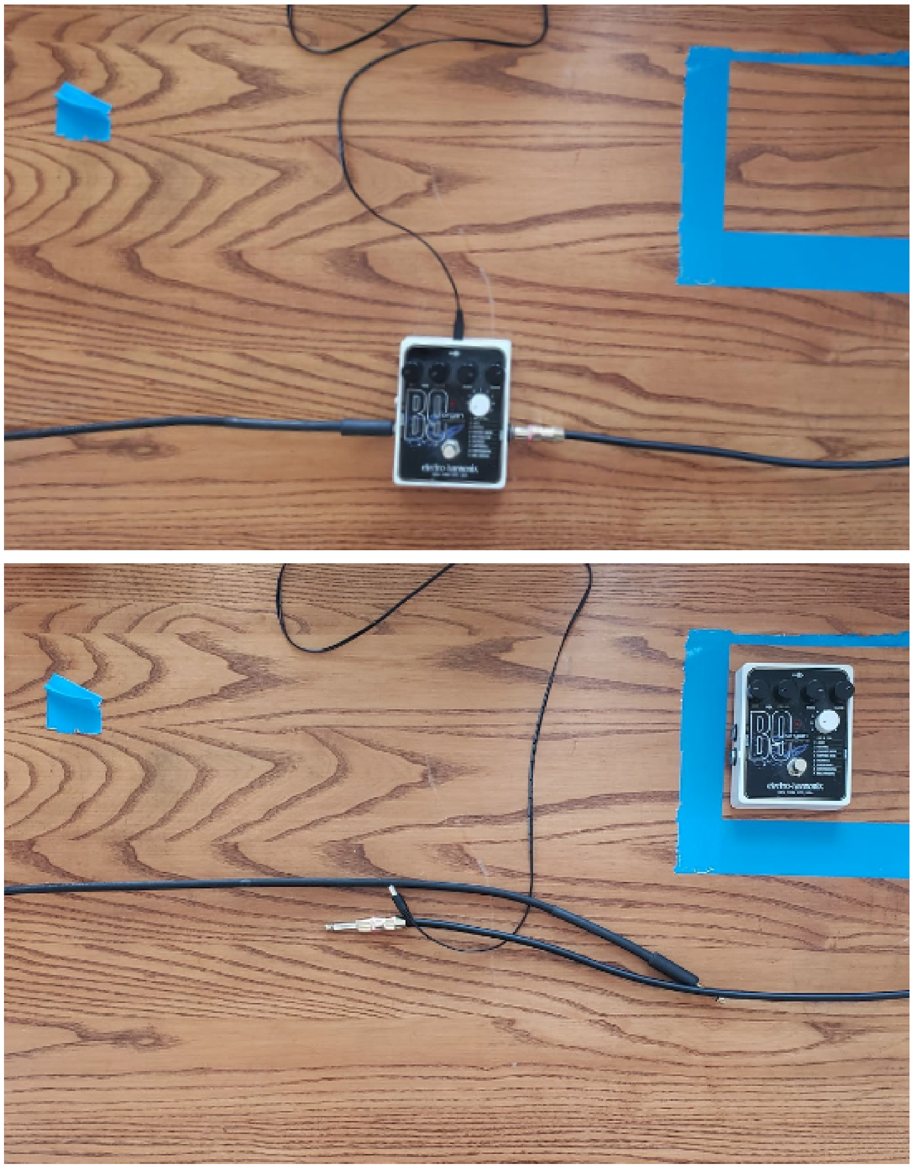


Figure 4.1: Swap Time Experimental Setup. Top: Starting and Ending position, with guitar pedal fully connected. Bottom: Unplugged position, with guitar pedal disconnected and placed in the blue box in the upper left. In this experiment, the subjects started in the fully connected position, moved to the unplugged position, touched the blue rectangle on left with one hand and then returned to the fully connected position. This imitates the process of swapping between two guitar pedals.

Type Name	Description
A	Standard sized pedal with side mounted jacks (similar to a Boss Compact pedal)
B	Standard sized pedal with top mounted jacks (similar to the EarthQuaker Devices Bit Commander)
C	Wide pedal with side mounted jacks (similar to Electro Harmonix B9)

Table 4.1: Set of three pedals used to represent the range of available products in the swap time test.

countdown to let the participant know when to start, the timer was started. From here, the participant disconnected the pedal, placed it in a rectangle marked on the table (shown in Figure 4.1 as the blue rectangle on the right), then proceeded to touch the second marker (the blue square on the left of the same image). This simulated the need for a user to grab a second pedal without the experiment actually requiring the use of two separate but identical pedals for each task. After touching this marker, the participant returned to the larger blue rectangle to grab the pedal and re-insert it into the signal chain, making the required input, output, and power connections. At this point, once, the participant placed their hands back on the guitar as if to continue playing to test the sound of this ”new” pedal, the timer was stopped and the time recorded. This measurement represents the time required to swap between pedals in the standard manual method.

The second test tests the hypothesis that the solution decreased the swapping time. This time the device was sitting on the table, with the instrument cable from the guitar plugged into its master input, and its master output connected to the input of a guitar amplifier. One of the pedals used for the control was connected to a plate (only one needed to be used for these tests because the mechanics of the swap event is the same regardless of which pedal is being used). Before the task began, this pedal and plate are inserted into one of the hot-swap connector receiving units. Again, the participant began with their hands on the guitar and followed the same sequence of steps as before, but this time instead of needing to unplug all of the cables, they needed only remove the plate from the receiver before placing it in the blue rectangle. During the second half of the task, they again needed only insert the plate into the receiver rather than plugging in cables.

Results

Six participants were used for this experiment, and each participant performed three trials of each task. Figure 4.2 shows the averages and standard deviations for each device tested, by participant. Visually, the plot indicates that there was a clear improvement in the hot swapping solution over all of the other pedals. It also appears that there were larger variations in the recorded times for the pedals than for the hot swapping solution. This might be because of the simplicity of the hot swapping solution. There is little place for error in inserting a plate into the hot swapping receiver, while when plugging in a pedal participants sometimes misaligned the plugs and jacks or even dropped the cable off the table, which is a realistic occurrence.

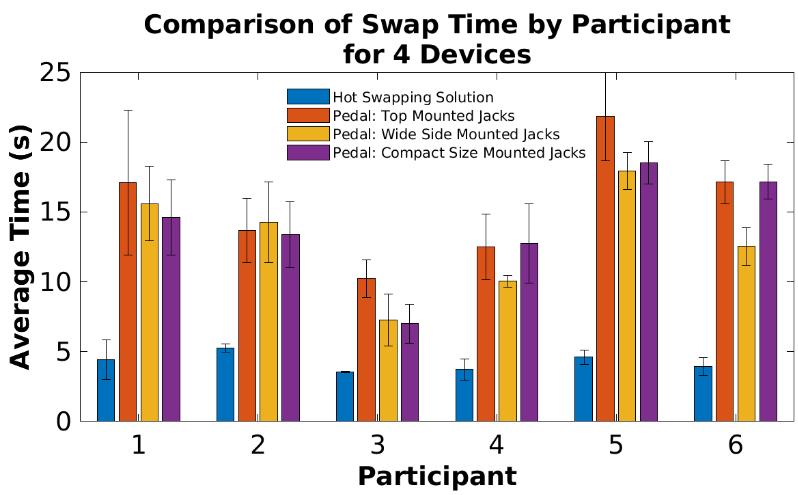


Figure 4.2: Swap time test data. Each participant performed the swapping test with three different standard effects pedals (shown in orange, yellow, and purple) as well as with the solution detailed in this report (shown in blue). The participants performed each test three times, and the average time is shown per participant with standard deviation bars included.

Analysis

In order to determine if the measurements show success or failure of the solution to meet the design requirements, this data must be synthesized into a single value. First, the measured times must be converted to a percent time savings by dividing the difference in time between using the hot swapping solution and a standard plugging method by the latter time as a reference:

$$r = \%\ \text{Reduction} = \frac{t_{\text{standard}} - t_{\text{solution}}}{t_{\text{standard}}}$$

These data sets are paired by participant, so the percent reduction in time must be calculated for each participant and for each standard pedal tested compared to the participant's time for the hot swapping solution.

Combining these values requires some sort of averaging, but taking a simple average would not be ideal, as each set of measurements has a different associated standard deviation. To minimize the variance in the final value, inverse variance weighting was used in taking this average, whereby data points with lower standard deviation are weighted stronger than data points with higher standard deviation. The weight w for a certain data point k with standard deviation σ is given by

$$w_k = \frac{1}{\sigma^2}\left(\sum_i \frac{1}{\sigma^2}\right)^{-1}$$

Then each time reduction data point r_k is weighted by its associated weight and summed to get the average reduction $\overline{R}$:

$$\overline{R} = \sum_i r_i w_i$$

Using this inverse variance weighting, the data indicates that the hot swapping solution has a 65% time improvement ($\sigma = 8.0\%$) over the standard method. While this fails to meet the design requirement, which called for an 80% improvement, it indicates that this solution method shows promise.

The swap time test provided a clue as to a direction for further improvement. Many participants had a hard time get the plate to mechanically align with the receiver, which increased the measured time for the solution. Although sliding one edge in place then letting the rest of the plate fall flat into the receiver is an effective method, this was not discovered by most participants on their own, and most attempted to keep the plate parallel to the table as they inserted it. A mechanical redesign of the receiver body to include features for guiding the plate into the correct position, including curved or slanted walls instead of right angles might help alleviate this issue and allow the hot swapping method to meet or exceed the 80% goal.

4.1.2 Compatibility

Because of the impracticality of physically testing the solution with many products, this compatibility requirement was designed for during the design phase of the project and thus no tests were conducted in this area.

4.2 Signal Quality Verifications

The second main category of system verification measurements are related to maintaining the same signal integrity as if the guitar were connected directly to the amplifier using an instrument cable. This allows users to make objective and unbiased comparisons between the products being tested.

4.2.1 Signal-to-Noise Ratio

Measurement Description

For this test, an Audio Precision System One (AP) measurement device was used to measure the noise floor of the device under test. The AP and associated software was used to send programmable test signals through the device and measure the resulting response. To measure the noise floor, the AP was programmed to output a sinusoid test signal and the amplitude was swept from $+10dBu$ down to $-100dBu$. This corresponds to a sweep from a $6.9Vpp$ signal down to $22\mu Vpp$.

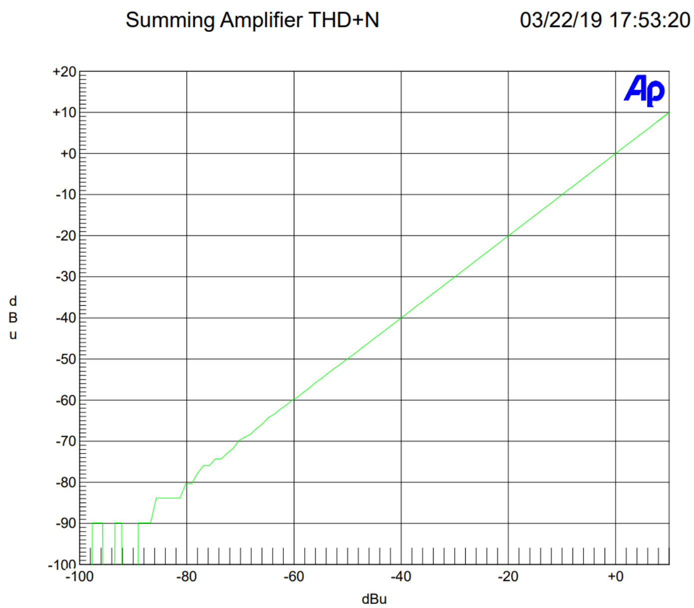
The plots in Figure 4.3 show the amplitude of the measured signal (in dBu) plotted against this swept test signal. When the test signal is above the noise floor, its amplitude dominates the output and the plot shows a straight line with a unit slope. However, when the test signal's amplitude goes below the noise floor, this dominates, and the slope goes to zero, indicating the level of the noise floor at the measured level of this flat part of the plot.

The first measurement made was a characterization of the AP itself, with its output and input connected with a two foot coaxial cable. Measuring the AP's own noise floor shows the limits of observation with this device.

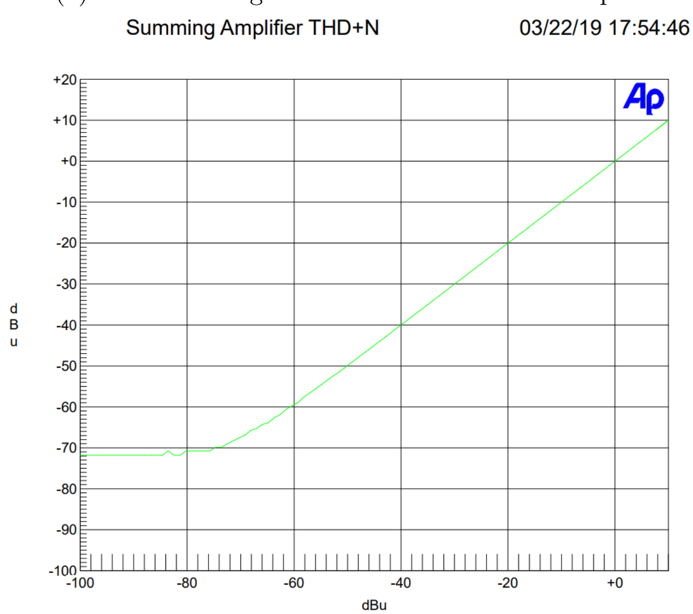
The important data measurements were then conducted. Two setups were used, as the signal path which passed only through relays was expected to have a different noise characteristic than the signal path which include the buffers and summing amplifier.

Results

During the first measurement, the external switching power supply which had been used was determined to be much more noisy than expected. During measurements for the



(a) *Direct* routing noise floor measurement output.



(b) *Summed* routing noise floor measurement output.

Figure 4.3: Example AP noise floor measurement plots. The x-axis shows the AP's test sinusoid output amplitude in dBu, and the y-axis shows the measured amplitude from the device under test.

prototype in the fall semester, it did exhibit some noise issues, but they were only marginally detrimental to the noise performance. However, during this test the power supply was demonstrating approximately a $77mV$ noise signal with a strong component near $330Hz$ (equivalent to $-29dBu$, which resulted in far worse measured noise floor than expected. The $330Hz$ location of the noise is not something that could be ignored because it is right in the fundamental frequency range of the guitar. With this in mind, this power supply was replaced with a bench top power supply that did not exhibit any issues. This lab power supply was used during the rest of the measurements to isolate noise from the device itself. This is not an unreasonable substitution, as an alternative power supply with a better specification could be easily switched out in the future to solve this issue.

Both the noise floor measurement from the *direct* signal path which only includes mechanical relays and the measurement from the *summed* signal pat is shown in Figure 4.4. The bars are referenced to the AP's own noise floor which sets the limit of this measurement. Lower values indicate better noise performance. As can be seen, the *direct* signal path performs very well, while the *summed* signal path has a higher noise floor.

Figure 4.3 shows two of the plots generated by the AP software. Note the strange oscillations in Figure 4.3a below $-96dBu$ which suggest that the device's noise floor may be reaching the limits of the measurement system (the plots generated during the characterization of the AP itself showed similar behavior). On the other hand, Figure 4.3b shows more normal behavior of the noise floor overwhelming the test signal.

Analysis

Of course, the noise floor is only one part of the signal to noise ratio; also required is the maximum signal amplitude. Although in theory the electro mechanical relays can conduct hundreds of volts, this would skew the results of this measurement as guitar pedals would not be expected to output that type of level. Instead, a reasonable estimation of the maximum signal level would be an $18Vpp$ signal, which would be the largest expected signal from the guitar pedals being tested, as $18V$ is the maximum output of the adjustable regulators supply power to the pedals. Although some pedals may have internal circuitry to boost their on-board supply voltages above this level, these are few and far between.

To compute the signal to noise ratio from the measured noise floor and the approximate maximum signal level,

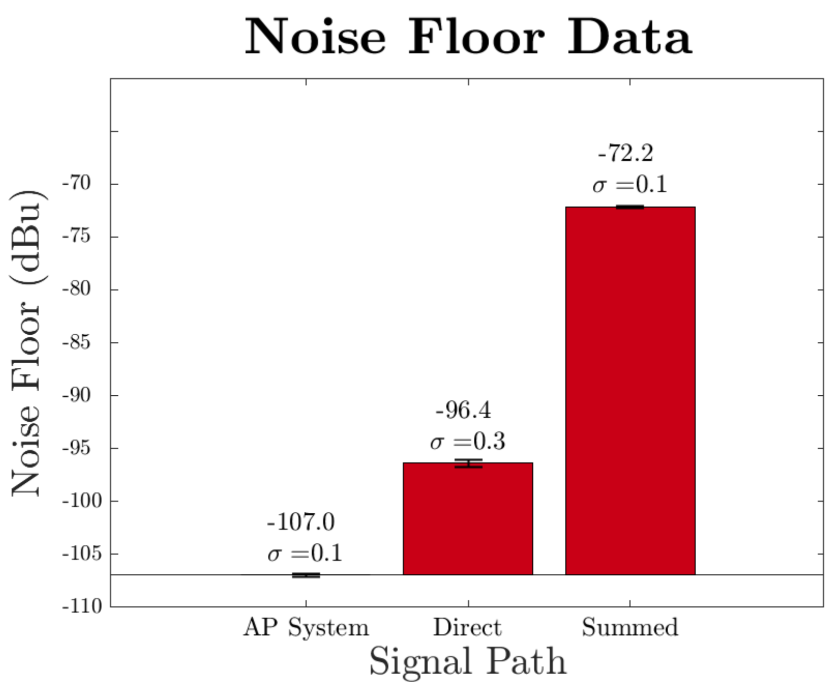


Figure 4.4: Results of the noise floor measurements. The AP's own noise floor was measured to be $-107dBu$. This was used as a reference value for the other measurements, so effectively the bars show the increase in noise floor over the minimum possible value to be measured; lower values indicate better noise performance. The *direct* signal path's noise floor was less than $10dBu$ off of the best measurable value, while the summing amplifier performed significantly worse at just $-72.2dBu$. For all of these measurements, $N = 20$ samples were taken.

$$\begin{aligned} SNR &= \frac{A_{max}}{A_{noise}} \\ &= \log(A_{max}) - log(A_{noise}) \end{aligned}$$

subtract the noise floor in dBu from the maximum signal level amplitude in dBu. With the two noise floor values recorded in Figure 4.4, the actual signal to noise ratio and can calculated:

$$\begin{aligned} SNR_{direct} &= 18.3 - (-96.4) = 114.7dBu \\ SNR_{summed} &= 18.3 - (-72.2) = 90.5dBu \end{aligned}$$

Both of these values exceed the design requirement of $90dBu$, though the *summed* path does not exceed it by much. These high signal to noise ratios, particular that of the direct, relay-only signal allows users to make informed decisions about the products they audition as they can be sure that this system adds negligible noise.

4.2.2 Frequency Response

Measurement Description

The AP system was also used to conduct this test. Again, the output of the AP was connected to the input of the device under test, and the output of the device under test was connected to the input of the AP. Here, the AP was programmed to output a sine wave sweep from $50kHz$ down to $10Hz$ at a $0dBu$ amplitude, at 51 discrete frequencies. The AP measured the amplitude of the resulting device output and plotted this against frequency.

Results

Again, the frequency response was measured for both the *direct* and *summed* signal paths. Figure 4.5 shows the results of the frequency response measurement for both signal paths. The *direct* signal path measurement in 4.5a is very flat down to the minimum frequency. In fact, the relays should work down to DC. There is a slight roll off in the upper frequencies mainly above $20kHz$ which could be due to loading from the biasing components used for the summing amplifier and associated buffers. On the other hand, the *summed* signal path does have a noticeable roll-off in the low frequencies, which appears to start around $100Hz$. This is a result of the decoupling capacitors used to bias the summing amplifier and buffers to the $A_{Vdd}/2$ virtual ground.

Analysis

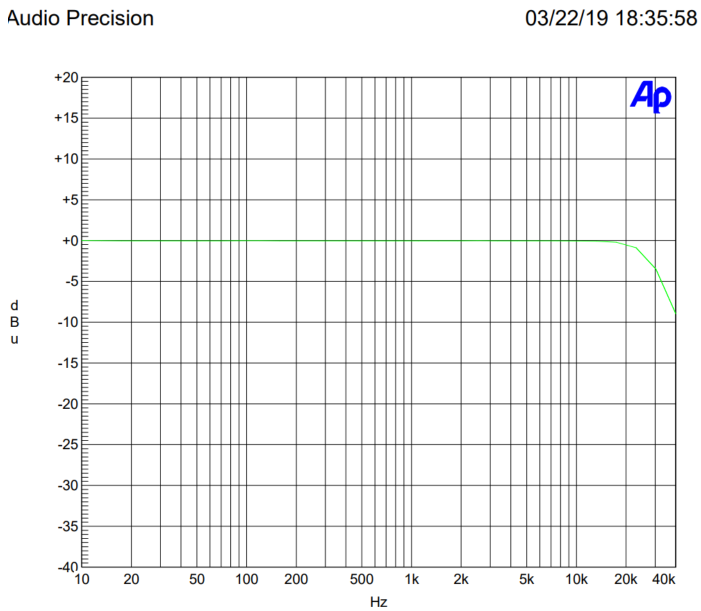
To determine if the results of this measurement demonstrate the success or failure of the device to meet the design requirements, the $0.1dBu$ flatness goal was superimposed over the data in the desired frequency range, as seen in . This was only performed for the *direct* routing configuration, as its accuracy is the most vital. The rationale for this decision is that when users are using the direct relay-only routing, they are most interested in making subtle comparisons between pedals, so a high performance signal quality specification is paramount. However, when they use the summing amplifier and splitting features, they are likely more interested in hearing the resulting sound from a combination of pedals, so the signal quality requirements can be slightly relaxed.

As can be seen in Figure 4.5a, the device meets this $0.1dBu$ flatness goal. It makes sense that at no point does the measured signal have a higher amplitude than the reference signal, as the device in this mode is totally passive. TThe dip in the low frequency is not a big issue, as it occurs around $12Hz$, which is below the audio spectrum, and it still falls within the desired flatness target.

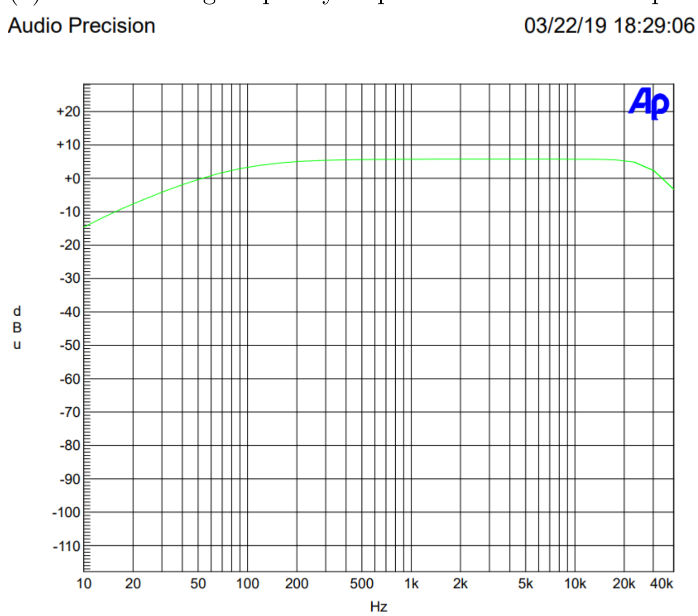
4.2.3 Switching Time

Measurement Description

The switching time was measured using the single-shot trigger function of an oscilloscope. Again the AP was used to output audio signals, in this case sinusoids on both of the channels. The device output was switched between a direct signal connection to one of the AP outputs and the sum of the two AP outputs. The trigger level was set higher than the maximum signal level of a single output but below the maximum amplitude of the summed signal. When the relay switched the output from the single signal to the sum, the oscilloscope triggered and stopped. The cursors were then used to measure the time difference between when the first signal is lost and begins to float back to ground and when the relay contact stops bouncing and makes solid contact to the second signal. To capture the relay switching in the opposite direction, one of the AP output signals was inverted so that when the two AP outputs were summed, they canceled, resulting in a lower output. This was used as the "first" signal, and the trigger level was set to trigger when the relay switched to a single sinusoid.



(a) *Direct* routing frequency response measurement output.



(b) *Summed* routing frequency response measurement output.

Figure 4.5: Example AP frequency response measurement plots. The x-axis shows the frequencies of the AP's test sinusoid output amplitude, and the y-axis shows the measured amplitude from the device under test. Although the high frequency roll off of the *direct* routing appears at first glance to be steeper than that of the *summed* measurement, the scale of the latter plot is longer, so it actuality they have the same slope. Also note that the flat level of the *summed* test is at $+6dBu$ rather than $0dBu$, which is a result of two $0dBu$ signals being summed. This means that the latter plot also confirms that the summing amplifier works correctly.

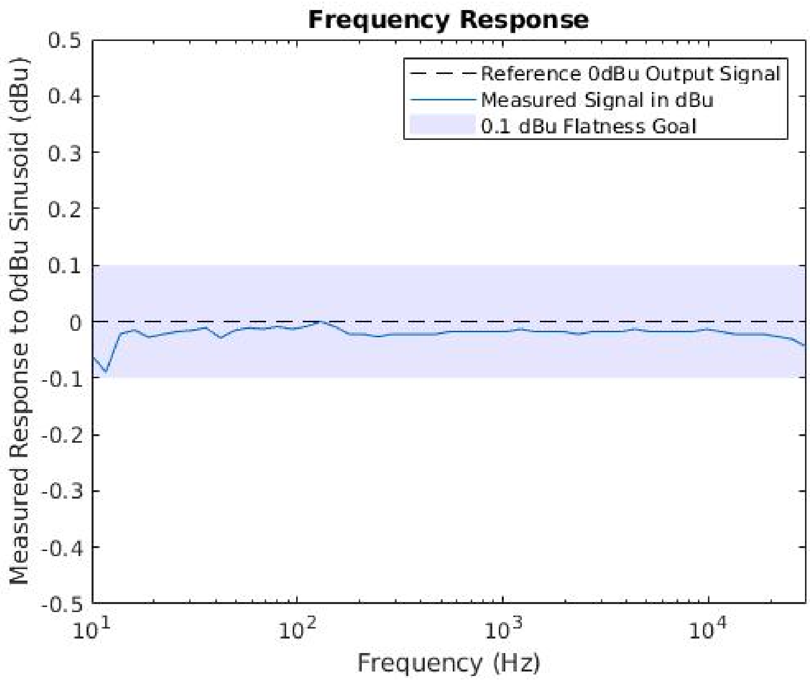


Figure 4.6: Frequency response of device in active send/receiver mode with signal routing using only relays. The $0.1dBu$ flatness goal is shown shaded in blue, while the recorded data from the device is plotted as the blue line. The dashed line at $0dBu$ was the reference signal output by the AP.

Results

Figure 4.7 shows one of the oscilloscope traces used to record the switching time measurements. Twenty trials of each switching direction were performed and their times recorded.

Figure 4.7: Example oscilloscope trace showing a relay switching event. This particular capture involved switching from a single signal to a summed signal. As can be seen at the far left (to the left of cursor a), the signal is a sinusoid with an amplitude around $0dBu$. To the right of cursor b shows the output after the signal switched to the summed signal (now with amplitude $+6dBu$). In between cursors a and b is the relay switching event. When the contact blade is disconnected at time a, the output floats back to ground for approximately $350\mu s$. After this, the relay blade begins to connect with the other contact, and the other summed output can begin to be seen. However it takes a full $\Delta t = b - a = 519\mu s$ before the bouncing appears to stop. In this trial, the $519\mu s$ was recorded as the switching time.

Analysis

Figure 4.8 shows the average switching times with the relays switching in both directions. Though there does appear to be some asymmetry when switching from one output compared to the other, the measurements show that the switching time is much lower than the $20ms$ goal, and will pose no issue with the signal cutting out.

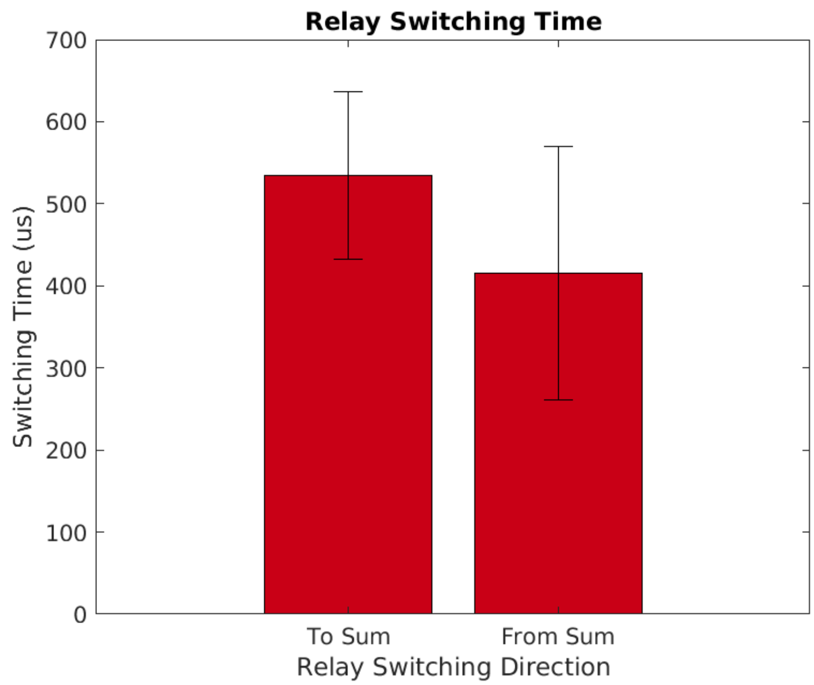


Figure 4.8: Comparison of average relay switching time in both directions, plotted with standard deviation. $N = 20$ for both measurements. Though there appears to be some difference in the switching times between the two directions, the main takeaway from this plot is that the both of these are far less than the $20ms$ requirement.

4.2.4 Switching Transient

Transients resulting from signal switching can arise from two main sources. The first is the system itself. This could result from some microphonic components in the system picking up the mechanical vibrations when the relay blade moves between the contacts. It could also result from the relatively large switching current driving the relay or other digital components coupling into the audio signal. If instead a solid state analog switch had been used, the charge injection resulting from stray capacitances in the MOSFET devices could cause a shift in level, resulting a transient when switched. The oscilloscope images show that the transient size is never greater than the instantaneous difference between the signals being switched, which demonstrates that the relays themselves do not add any transient.

The other type of transients are related to the signals themselves that are being switched.

Any instantaneous difference in level will result in a transient of some sort. The worst possible case would be two signals 180° out of phase being switched at the moment they have reached their maximum. This would result in a transient the size of the signals' amplitude. Because of time constraints and a desire to avoid adding complexity to minimize signal quality issues, no mitigation circuits were designed to reduce this type of transient. Measuring this type of switching transient is difficult to glean meaningful data from because of this dependence on the exact signals being switched, so no there was no further exploration of this area during this project.

Chapter 5

Budget

Chapter 6

Conclusion

6.1 Comparing Built Specifications to Design Requirements

6.2 Future Work