INITIAL TECHNOLOGY REVIEW

Final Revision

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ABSTRACT

This report presents a review of the technology for which the Author intends to develop a digital simulation. The technology being treated is the original Leslie rotary loudspeaker. The Leslie rotary loudspeaker is an analogue electromechanical system utilizing rotating sound sources to modify sound which is passed through it. Included in this report is a consideration of prior art in digital simulation of the Leslie rotary loudspeaker and recommendations for further development thereof. The intended digital simulation platform for further development is functional script for the Matlab R2011b environment.

1. INTRODUCTION

Invented by Donald Leslie, the first Leslie rotating speaker systems were produced in 1941. The Leslie speaker consists of two independent loudspeaker drivers each acoustically coupled to two independently rotating assemblies. The bass driver fires down into a rotating cylindrical baffle, while the high frequency driver fires upwards into a rotating horn assembly (consisting of one radiating horn and one dummy horn to balance the rotating assembly). Both driver/rotational assemblies are housed within a large wooden cabinet which is integral to the sound of the Leslie.

The Leslie speaker became ubiquitously synergistic with the Hammond organ in particular, and was also very commonly interfaced with the Wurlitzer organ and other early organs as well as with the electric guitar. Since its inception, the Leslie speaker or effect has been used in increasing creative ways. For example, the Beatles song ‘Blue Jay Way’ features both Hammond organ and backing vocals each reproduced through Leslie speakers.

Originally the Leslie speaker allowed the rotational speed to be selected as stationary (zero rotational speed / off), low speed or high speed and was controlled by a simple switch mechanism mounted to the organ. The rotating bass assembly would take longer to spin up and spin down due to its larger mass relative to the rotating treble assembly; however the Leslie was designed such that they would each have the same maximum rotational frequency.

2. PHYSICAL EFFECTS OF ANALOGUE SYSTEM

The Doppler Effect is the effect governing the compression or rarefaction of wavelength due to a moving sound source. This effect is commonly experienced when an emergency vehicle quickly drives past a listener with siren blaring. The siren is heard to increase in pitch as the vehicle approaches the listener and to decrease in pitch as the vehicle retreats. This is because, relative to the listener, the wavelength of the emitted sound is compressed as the sound source accelerates towards the listener. Conversely the wavelength of the emitted sound is expanded as the sound source accelerates away from the listener. It is this physical Doppler Effect which is most fundamental to the resultant sound effects generated by a Leslie speaker and is manifest in the property of vibrato or frequency modulation.

In a Leslie speaker, the physical means by which the Doppler Effect is produced involves rotating sound sources. This creates another physical effect exploiting the directionality of the sound sources. Because the sound sources in the Leslie are significantly directional, as a source rotates away from the listener, the amplitude and perceived volume decreases. Conversely, as a source rotates towards a listener, the amplitude and perceived volume increases. This manifests as the property of tremolo or amplitude modulation.

The abovementioned vibrato (frequency modulation) and tremolo (amplitude modulation) properties are both results of the same physical effect and therefore the modulation of each property are governed by the same parameters. Because the physical effects are due to circular rotational motion, the modulation function is necessarily sinusoidal, the frequency parameter of which is common to both manifest properties.

The cabinet of the Leslie Speaker in which the rotating speaker assemblies are housed, acts to ‘contain’ the produced sound in a relatively reverberant environment. The cabinet is ported around its circumference so as to allow the sound to propagate in a controlled manner (somewhat omni-directionally). This cabinet system has the effect that all the Doppler affected sound generated within the Leslie cabinet is allowed to reflect and additively combine as and before it leaves the cabinet. Due to the slight delays inherent in the sound reflecting from various surfaces within the cabinet and emanating from the sound sources in various directions, the additive combination gives the impression of emanating from multiple, perhaps many, sources. This property is commonly known as Chorus effect, and is a more subtle but intrinsic aspect of the Leslie sound. The delayed reflections which generate the property of Chorus effect also generate to some degree the property of Phasing (or Flanging) effect due to comb filtering generated by the addition of these delayed reflections and delayed direct propagations of sound. These Chorus and Phasing properties are more subtle but the Author suspects are critical to a realistic simulation of the sound of the Leslie rotating loudspeaker.

As stated in the introduction, the Leslie speaker consists of two separate drivers, each reproducing exclusively bass or treble. Due to the difference in mass between the rotating treble horn assembly and the rotating bass baffle assembly, each exhibits differences in acceleration and deceleration.

Because the Leslie speaker was originally powered by single ended triode amplifiers (valve amplifiers), overdrive distortion (which was a common occurrence) generated predominantly low, even order harmonics lending a warm, gritty and authoritative sound to the instrument being amplified. Even in the absence of overdrive distortion, the total harmonic distortion (again predominantly low even order harmonics) inherent to the single ended triode valve amplifier would have been characteristic of the Leslie sound.

Finally, The Hammond organ was commonly amplified through two independent Leslie speakers for stereo miking techniques. The properties of this effect are more manifest in recorded material than live but are just as important to the range of Hammond/Leslie sound experienced throughout the history of this symbiotic musical-technological relationship.

Overall, in descending order of importance, the following properties are believed to collectively constitute the ‘Leslie sound’:

- Vibrato
- Tremolo
- Chorus
- Phasing / Flanging
- Acceleration disparity between drivers
- (Low-even-order) Harmonic Distortion (from Leslie single-ended valve amplifier)
- Stereo effects (from miked dual Leslies)

3. PRIOR ART

A cursory literature review was undertaken to explore existing developments in the Matlab simulation of Leslie rotary loudspeakers. Due to limited treatment in the literature, two publications were acquired and reviewed.

The book Dafx Digital Audio Effects by U. Zolzer yielded some methodological examples; however no Matlab implementation. By following the methodological examples attributed to S. Dish and U. Zolzer, and piecing together Matlab implementation of its constituent effects (namely vibrato and tremolo) found elsewhere in the book, the Author was able to execute what was expected to approximate Dish and Zolzer's proposed Leslie simulation. Upon investigation of the simulation, the Author found its effects to be severely lacking as an accurate representation. This is believed to be due to the inclusion of vibrato and tremolo exclusively ignoring the other subtle effects identified in 2 of this report. In addition, the tremolo was modulated by a triangle wave and the modulation frequency was not coherent; however this shortcoming was due to the Authors limited cursory development of the script. The methodology presented by Dish and Zolzer is flawed in that it assumes only a single driver is responsible for all frequency in the Leslie, and that this driver radiates through two horns, positioned oppositely on the same axis. In fact in the real Leslie speaker, one horn is simply a dummy acting as a counterweight to balance the spinning assembly (and this horn reproduces only treble).

A Stanford University paper published in the proceedings of COST-G6 Conference on Digital Audio Effects, entitled 'Doppler simulation and the Leslie' by J. O. Smith, S. Serafin, J. Abel, and D. Berners was identified for review. As this paper covered a more in depth treatment in simulating the physical effects of the Leslie, J. O. Smith's book Physical Audio Signal Processing (For Virtual Musical Instruments and Digital Audio Effects), covering the results (and background) of this paper, was purchased for review also. In his book, Smith treats the topic of Leslie speaker simulation from the standpoint of measured observations and the physical equations characterizing rotational source velocity and the Doppler shift. Smith also treats the simulation as two separate entities characterizing the rotating horn and the rotating woofer baffle. Inclusion is made also of reflections in the cabinet characterized as multiple image sources for the first reflections with the addition of artificial reverb for latter reflections. Smith cites that an 'AM-throb' is the main constituent effect of the rotating woofer baffle and that this has been achieved by others using a low-pass filter with modulated cut-off frequency.

Smith's book and paper treat the Leslie simulation from a mathematical standpoint utilizing interpolating delay-line writes; however provide no Matlab scripted examples. Nonetheless, Smith's work stands as a strong reference for the Authors further development in this field.

4. RESULTS

The following results are those generated in the cursory examination of Matlab script as was pieced together from Zolzer's text. The basic principles that will underpin further development are illustrated, as are the shortcomings in this basic method.

4.1. Tremolo

The tremolo Matlab function works by generating a vector array characterizing a low frequency oscillator (LFO). In this particular script, the LFO is based upon a triangular wave modulation between -0.5 and 0.5, of specified resolution (according to input parameter "step"), and of length equal to the input file. This LFO vector is then multiplied by the input file in a piece-wise manner, resulting in a multiplication or modulation of the amplitude of the input file by the LFO vector.

The tremolo effect can be expressed mathematically as the multiplication of the gain of an input signal, by a periodic LFO signal:

$$x_{out}[s] = z_{LFO}[s] \cdot x_{in}[s]$$

Figure 1 shows the original input signal 'sample.wav' in blue with the tremolo affected signal superimposed in green. The triangular amplitude modulation is clearly apparent.

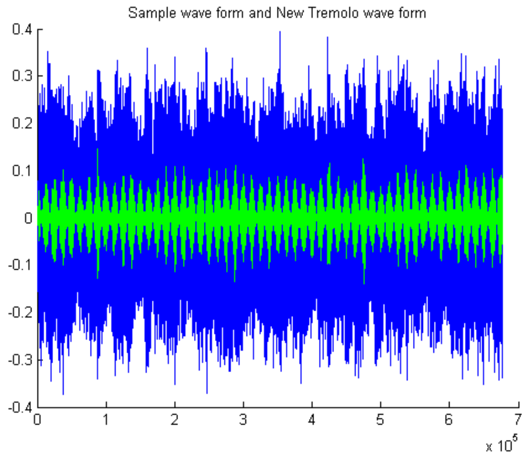

Figure 1. *Sample waveform in blue with applied tremolo waveform superimposed in green.*[i]

4.2. Vibrato

The vibrato Matlab function has subtle complexities in its operation and is therefore relatively difficult for the Author to understand. It appears, as explained in DAFX ch. 2.6.1, that a pitch variation is generated as a result of a variation in delay. Because the delay is due to a periodic source, the delay duration is modulated by a periodic source which again is implemented as an LFO. The LFO sweeps the delay across a set range of duration at a set frequency. This practically manifests as a frequency modulation. Only the delayed signal is output and this is perceived as a periodic variation in pitch to the listener.

The vibrato effect can be (conceptually) expressed mathematically as the multiplication of the frequency of an input signal, by a periodic LFO signal (although this is not how the effect is implemented). Assuming the input signal is a sinusoid:

$$x_{out}[s] = sin_{x_{in}}[z_{LFO}[s] \cdot 2\pi \cdot \omega \cdot s]$$

Figure 2 shows the input signal to the vibrato function, (which is in fact the previous output from the tremolo function) in blue with the vibrato affected signal superimposed in red. It is less clear than the tremolo example; however a frequency modulation is still apparent in figure 2. The amplitude modulation applied earlier remains apparent also.

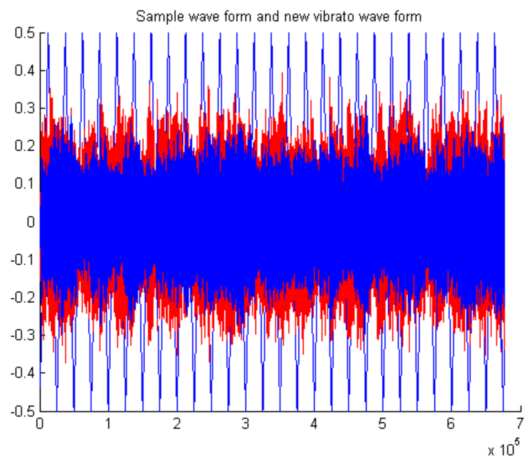

Figure 2. *Tremolo output waveform in blue with applied vibrato waveform superimposed in red.*[ii]

5. RECCOMENDATIONS

5.1. Improvements

Following the examples set out by Smith, a significantly more realistic Leslie speaker simulation is expected to result from the inclusion of all the various 'subtle' properties outlined in section 2 of this report. The Author, due to time and resource constraints, intends to simplify Smith's approach somewhat and aim for a resulting complexity somewhere between Smith's and Zolzer's respective treatments. Further to Smith and Zolzer's treatments, the Author has identified additional peripheral effects such as that of Single Ended Triode amplifier distortion and stereo effects due to two Leslie cabinets that the Author deems worthy of inclusion.

5.2. Proposed Inclusions

Summarily, the following properties are proposed for inclusion in descending order of fundamental importance:

- Adjustable frequency sinusoidal modulated vibrato (adjustable depth)
- Adjustable frequency sinusoidal modulated tremolo (adjustable depth)
- 'Modulation frequency lock' for above vibrato and tremolo features or ability to vary modulation frequencies independently
- Ability to vary relative volume of abovementioned vibrato and tremolo features
- Variable intensity Chorus effect, with variable relative volume
- 'Single ended triode' amplifier THD and overdrive distortion simulation
- Adjustable intensity and volume of above distortion simulation feature
- Adjustable harmonic inclusion of above distortion simulation feature
- Optional simulation of disparity in acceleration of drivers
- Optional Stereo effect (simulating independent Leslie effect per channel)

5.3. Proposed Implementation

The effect simulation proposed herein will be implemented as a functional script in the Matlab R2011b scripting environment. It will operate sequentially on an input audio file and produce an output audio file. Inputs to the function will include the audio wave file to be affected as well as a range of parametric inputs characterizing the abovementioned properties. Outputs of the function will be limited to the resultant affected audio wave file, with the possibility of parametric outputs indicating the state of the simulation for the given output audio wave file.

The signal flow diagram of Figure 3 crudely demonstrates the proposed implementation and is subject to further development and refinement. Notice the frequency modulation component of the Vibrato and the amplitude modulation component of the tremolo. Superimposed instances of small, random delays are incorporated to generate the Chorus effect as discussed earlier in the review. These may or may not require sinusoidal modulated frequency variance as in the vibrato delay structure.

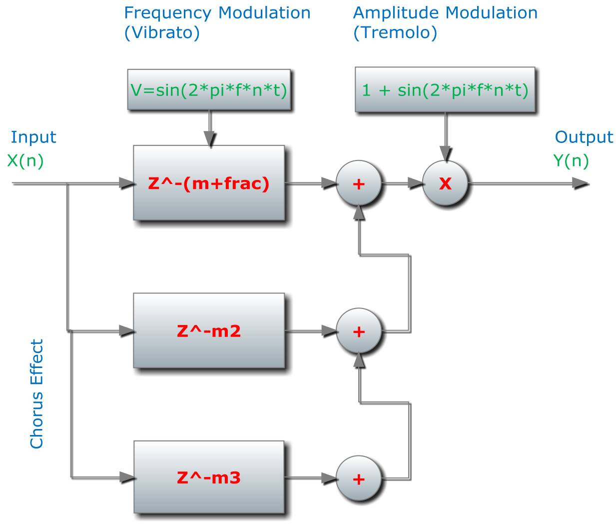

Figure 3. *Crude signal flow diagram for proposed implementation.*[iii]

6. CONCLUSION

The Author stands well prepared to begin further development of a Matlab simulation of the Leslie rotating loudspeaker. Several recommendations have been identified for inclusion in the ensuing project with the expectation of improved results compared to the cursory examination of existing Matlab examples in the prior art. By incorporating the research of Smith *et al*. with the basic principles demonstrated by Zolzer *et al*. a significantly realistic and yet not overly complex simulation is intended to be achieved.

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[i] Figure 1 was generated by script using Matlab R2011b
[ii] Figure 2 was generated by script using Matlab R2011b
[iii] Figure 3 was generated using SmartDraw 2010.05