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Research Article in Physics

How Does the Input Signal Shape Affect the Pass Efficiency After Stochastic Resonance?

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Abstract:

Stochastic Resonance is a phenomenon first discovered in 1981. The phenomenon describes that under certain conditions, in a non-linear system, a noise added to an input can make the input signal pass the non-linear barrier. This study will investigate how the shape of the input signal wave can affect the output efficiency. A circuit with a noise source, an AC source, a Schmitt trigger (act as the non-linear system) is simulated. Various shapes of the wave were tested in the simulator, which resulted in different spectrums and voltage-time graphs of the output and output efficiencies. After comparing the results for different wave shapes, the pulse wave and the square wave are observed to have the highest output efficiency and signal-to-noise ratio, followed by sinusoidal wave, triangular wave, and sawtooth wave in that order.

Keywords: Schmitt Trigger, Stochastic Resonance, Noise, Signal Shape

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1. Introduction

Stochastic resonance was originally a theory developed by Benzi R. et al. in 1981 (Benzi, 1981). The theory proposed that a noise added to a signal wave might enable a signal to pass through a non-linear bistable system. For a weak signal that originally can't pass through a signal barrier, adding a noise under certain conditions will enable it to be detected.

Stochastic resonance exists for waves in different mediums. Originally Benzi R. et al. discovered it in periodic behavior of the climate (Benzi, 1982); in 1983 it was discovered by S. Fauve et al. that it exists in voltage signals (Fauve, 1983). In 1991 F. Moss et al. discovered this phenomenon in neurons (Moss, 1991).

Previous researches investigated other factors that will affect the signal-to-noise ratio (SNR) of the signal in stochastic resonance. For example, S. Fauve et al. in 1983 discovered that the signal-to-noise ratio is correlated with the noise variance (Fauve, 1983). However, there isn't any previous research on how the specific shape will affect the output efficiency. Thus, this paper focuses on comparing the output efficiency for different wave shapes, such as square wave, sinusoidal wave, etc.

It is hypothesized that there is a change in the output efficiency of the signals as the shape of the wave changes. The type of correlation between the independent variable and the dependent variable is not quantitative but qualitative since the input is the "shape" of the signal input. The research question is to investigate how the output efficiencies are different for waves with different shapes.

2. Research Design, Data collection and analysis Methods, Materials

The experiment described below is used to measure the output efficiency of the signals after stochastic resonance.

2.1. Design of Study

The circuit used in simulation is demonstrated in Figure 1, and the simulation was done using Falstad Circuit Simulator (www.falstad.com/circuit).

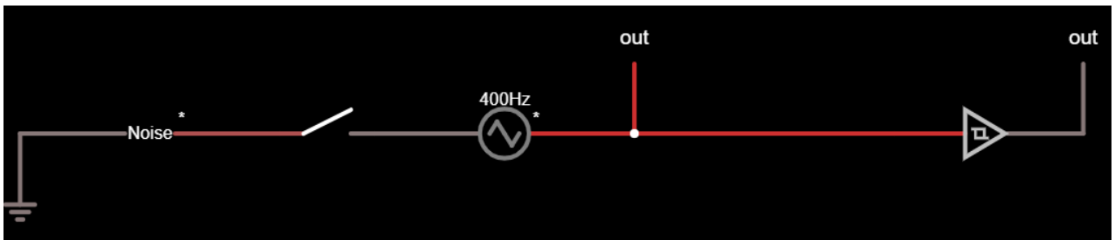


Figure 1. The circuit diagram of the simulated circuit.

The circuit diagram is shown in Figure 1 above.

From left to right, the components of the circuit are:

1. Ground (to make sure that the starting voltage is 0)
2. A noise producer (the noise voltage is added to the 0 voltage from the ground)
3. A switch (to investigate what happens with and without the noise producer)
4. A 2-terminal AC source (to add to the noise voltage, the shape of the voltage wave will be changed to investigate the difference in outputs)
5. An analogue output (used to show the voltage wave shape before the barrier – in 6)
6. A Schmitt trigger, to simulate a non-linear barrier.
7. A second analogue output (used to investigate the voltage wave shape after the barrier)

2.2. Data collection and analysis methods

2.2.1 Procedure:

1. Access to the Falstad Circuit Simulator. (www.falstad.com/circuit)

2. Create a circuit shown in the section "Research Design", electric components can be created using the drop box after clicking "Draw" on the top left corner as shown in Figure 2.

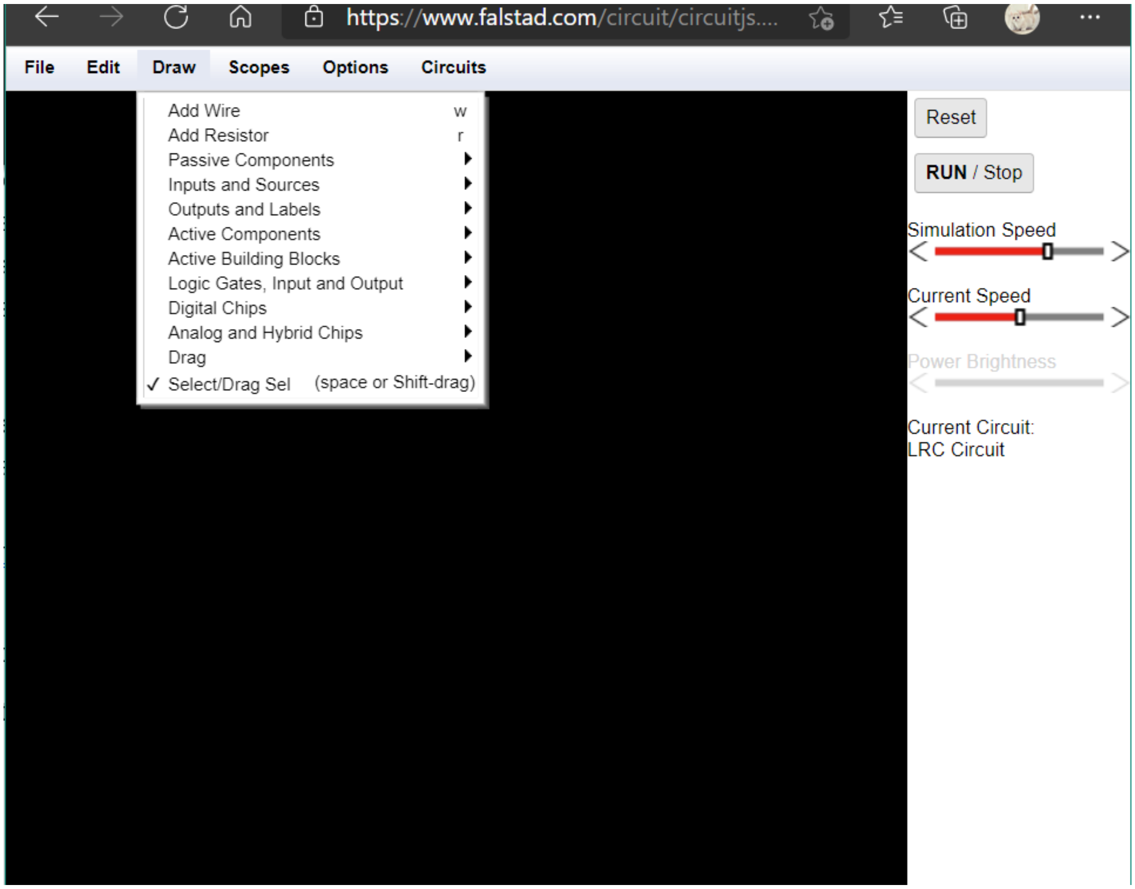


Figure 2. The GUI of Falstad Circuit Simulator, showing the drop box of components.

3. The simulator allows configurations for the components. Right click a component and left click "Edit" for configuration as shown in Figure 3. In this research, some values of the configuration were set to constant, while some other were variated.

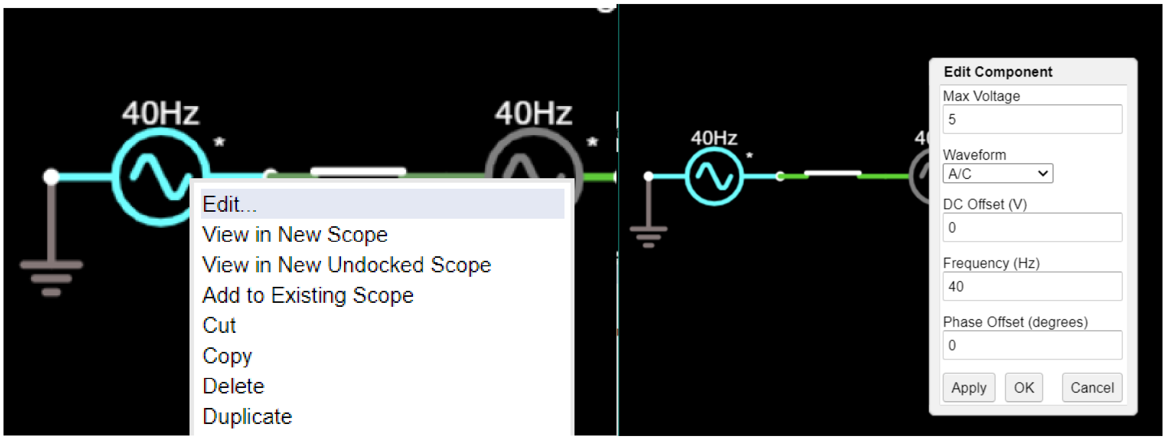
Constant configurations that are not default:

a. The Maximum Voltage of the AC Source Producer: 3.5V
b. Frequency of AC Signal Source: 400Hz
c. Lower and Upper Threshold of the Schmitt Trigger: 2V & 5V

Specific non-constant configurations will be described in Section 3 (Result), those are:

a. Waveform of the AC signal source
b. Maximum Noise Voltage (MNV)

Note: A noise producer is created by changing the "waveform" configuration of a 2-terminal AC source to "Noise".



(a) (b)

Figure 3. How to configure a component (a) Dropbox after right-clicked a component (b) An example of a configuration page: AC source

2.2.2 Input and Outputs

The input refers to the voltage over time that enters the Schmitt trigger, this maybe signal + noise, or only signal. The input voltage was presented in two ways: a time-domain graph (TDG) and a frequency domain graph (FDG).

The output voltage refers to the voltage over time that exists the Schmitt trigger. This will be also presented by a TDG and an FDG.

In the simulator, both graphs can be viewed in a "scope" which is presented by right click the two "analog output" components and then click "View in New Scope" as shown in Figure 3(a).

Five different input wave shapes were tested:

1. Pulse Wave
2. Sinusoidal Wave
3. Triangular Wave
4. Square Wave
5. Sawtooth Wave

For each of the waves, two scenarios: with and without noise, were simulated.

2.2.3 Processing of Output

The output efficiency is usually determined by the Signal to Noise Ratio (SNR) in past studies. However, due to the limitation of the Falstad Simulator, the output graph can only be viewed as a graph but cannot be exported to a table containing numerical values. Thus, the output graphs will be analyzed qualitatively.

3. Results

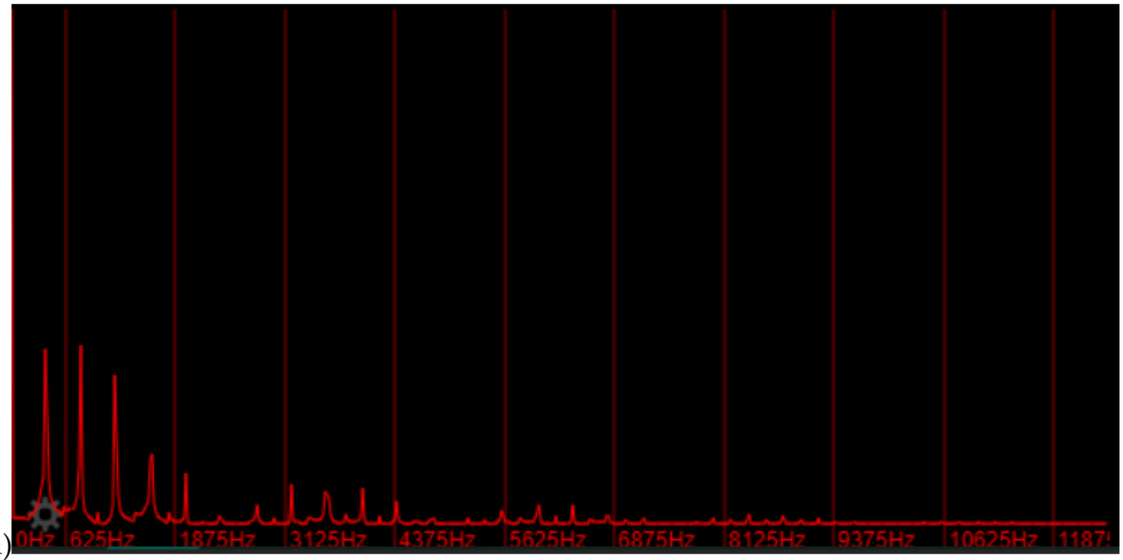
3.1. Input and Output Data

Note: The spectrum graphs are not in scale, due to the limitation of the simulator.

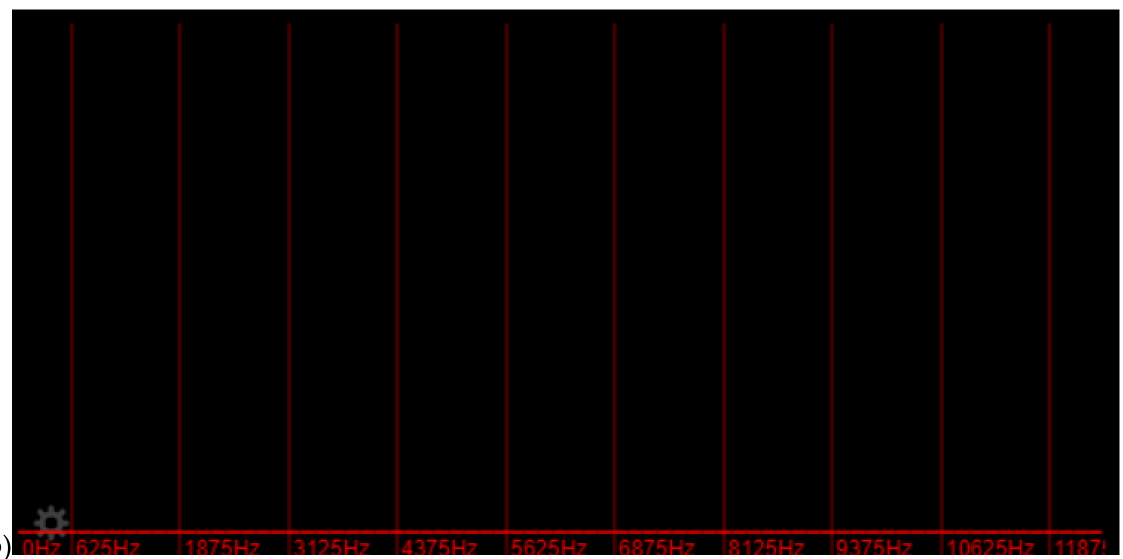
<u>Pulse Wave:</u>

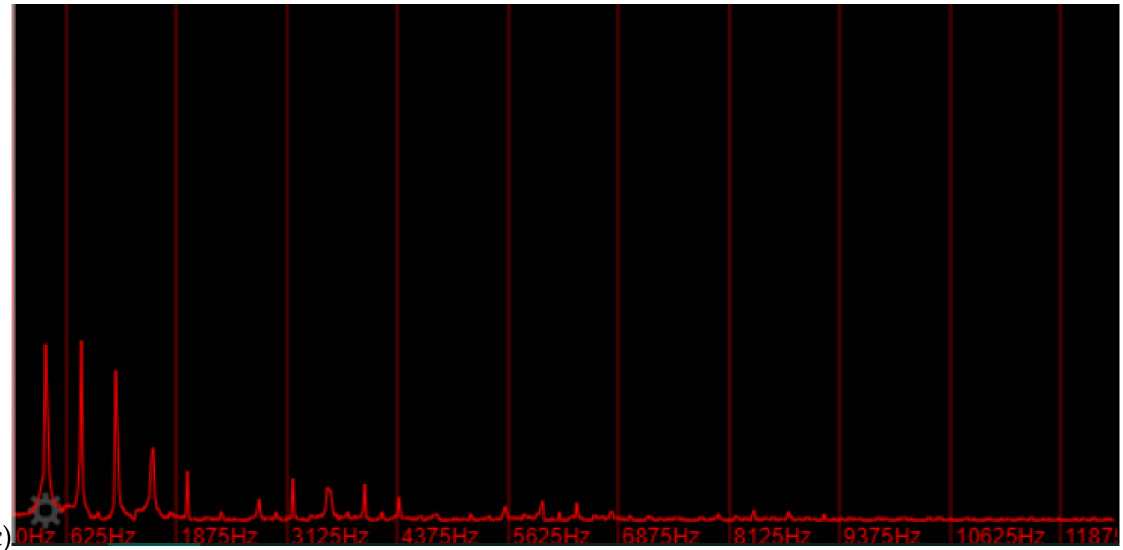
MNV = 3V

(a)

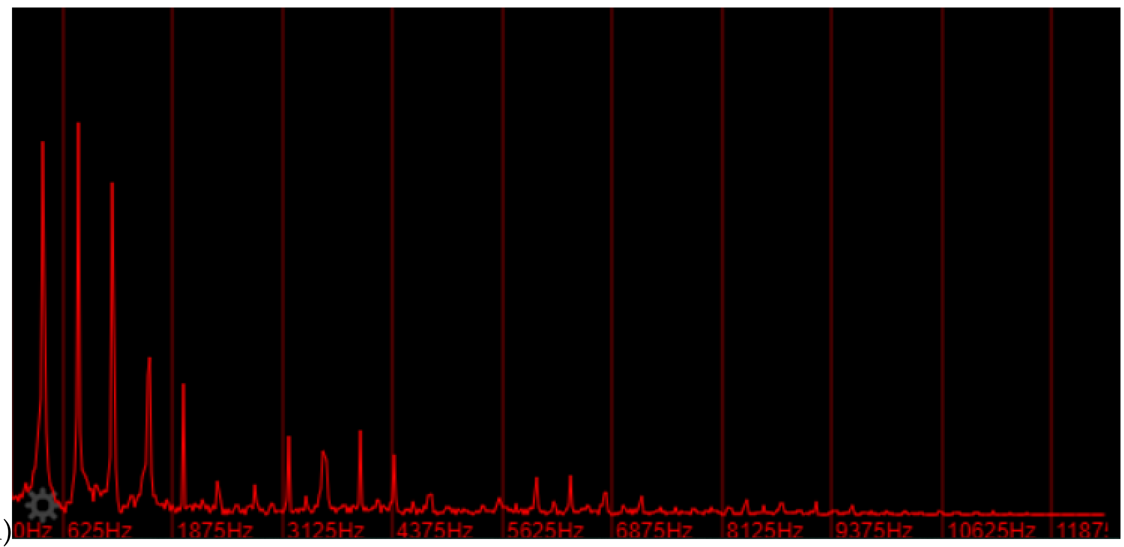


(b)





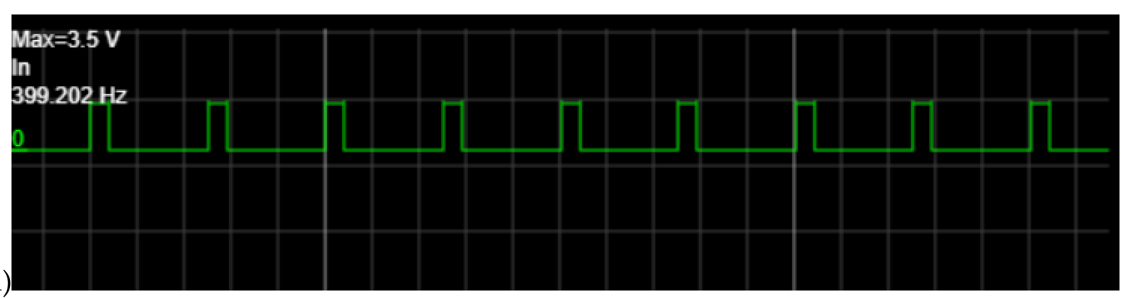
(c)



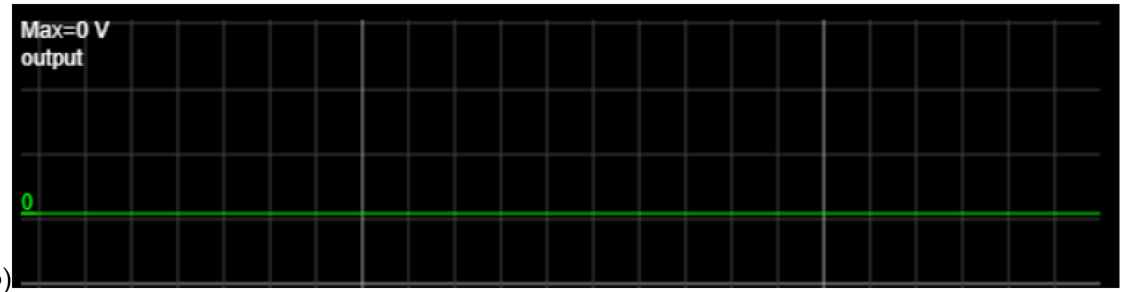
(d)

Figure 4. FDG of (a) input without noise (b) output without noise (c) input with noise (d) output with noise

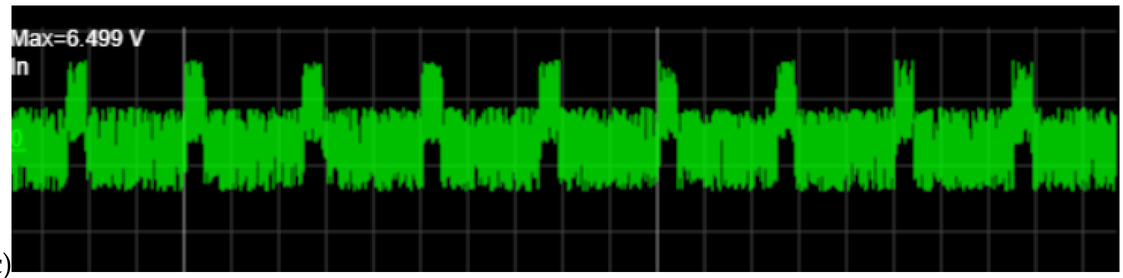
From Figure 4, it can be seen that the spectrum for the original signal (a) with the output after adding noise (d) look very similar. This may suggest that the output efficiency is very high.



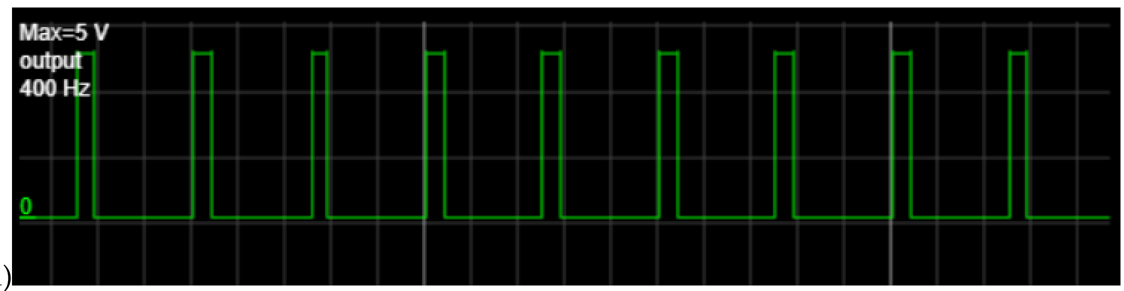
(a)



(b)



(c)



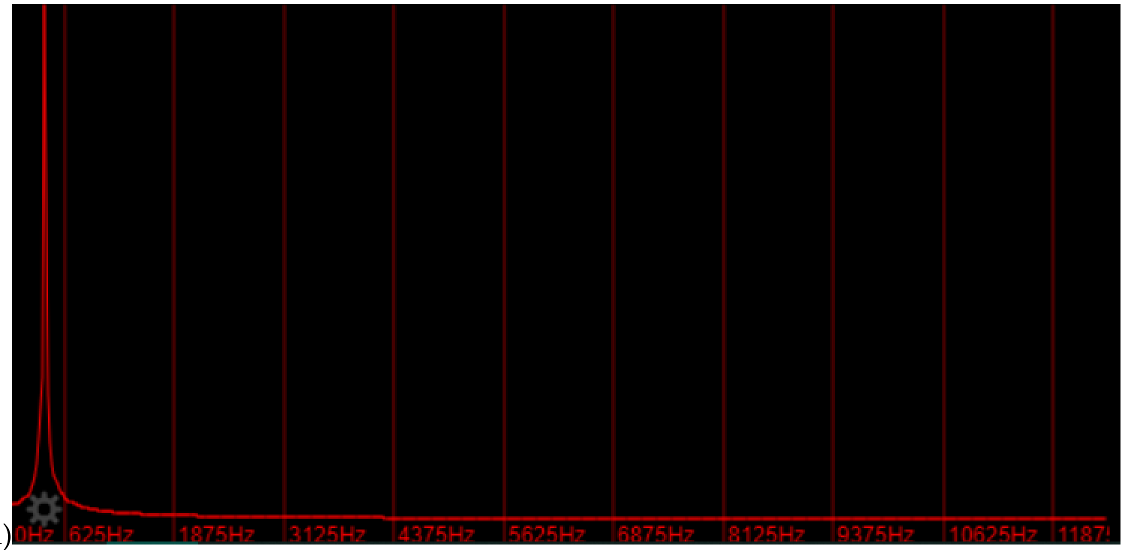
(d)

Figure 5. TDG of (a) input without noise (b) output without noise; (c) input with noise (d) output with noise

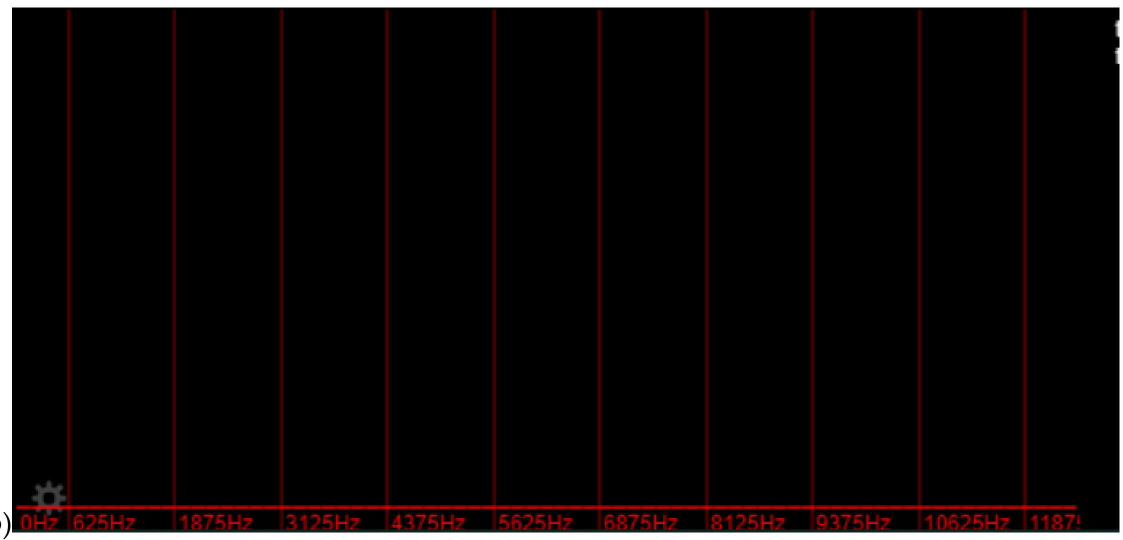
Figure 5 further proves the finding from Figure 4. The voltage-time graph of the output after noise is added (d) is the almost the same with the graph of the signal (a), except that the maximum voltage is 5V for output and 3.5V for input.

Regular AC Wave (Sinusoid):

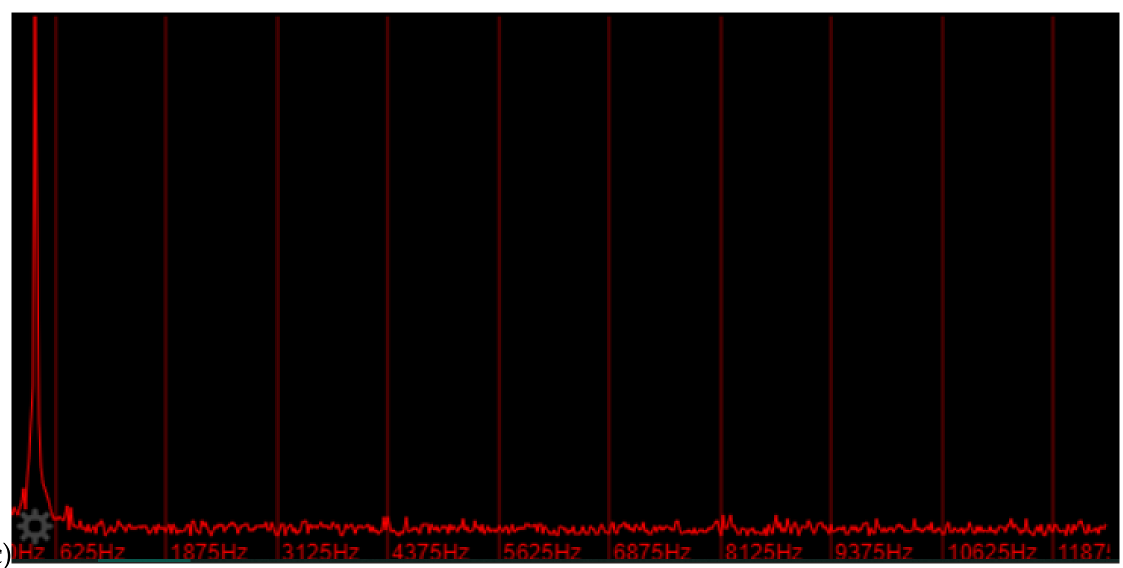
The MNV is 5.5V


0Hz
625Hz
1875Hz
3125Hz
4375Hz
5625Hz
6875Hz
8125Hz
9375Hz
10625Hz

(a)


0Hz
625Hz
1875Hz
3125Hz
4375Hz
5625Hz
6875Hz
8125Hz
9375Hz
10625Hz

(b)


625Hz
1875Hz
3125Hz
4375Hz
5625Hz
6875Hz
8125Hz
9375Hz
10625Hz

(c)

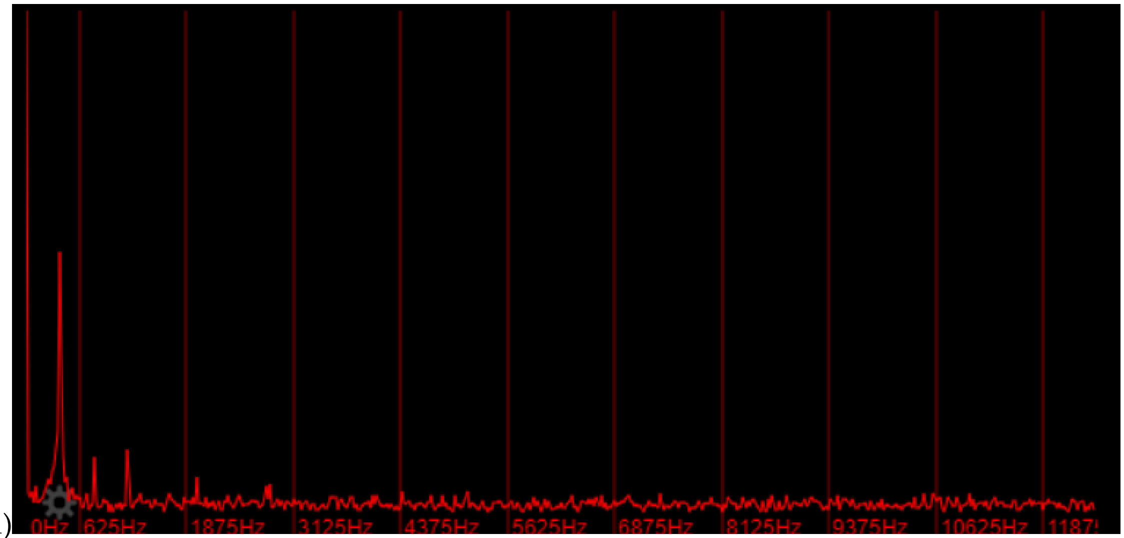
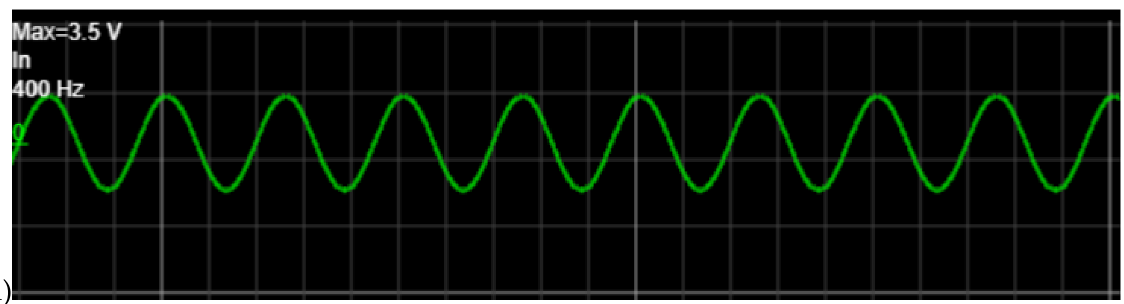
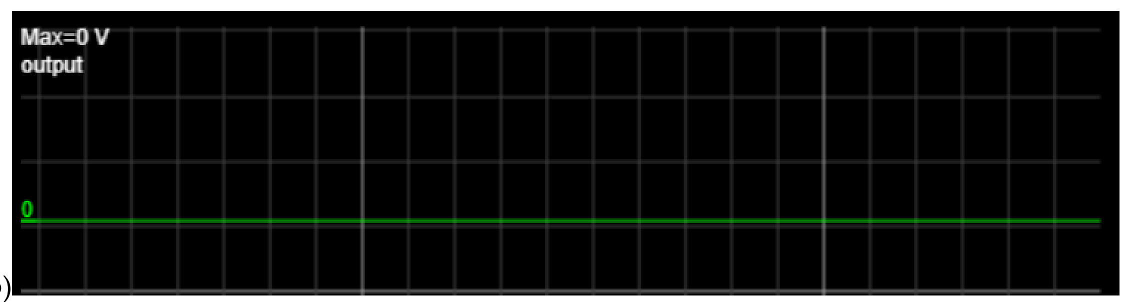
(d) 

Figure 6. FDG of (a) input without noise (b) output without noise; (c) input with noise (d) output with noise

From Figure 6, it can be seen that the spectrum of output (d) with noise and the original signal (a) has a common peak at 400Hz, but some noise can be seen from (d) as well, such as the small peaks at around 800Hz and1300Hz.

(a) 

(b) 

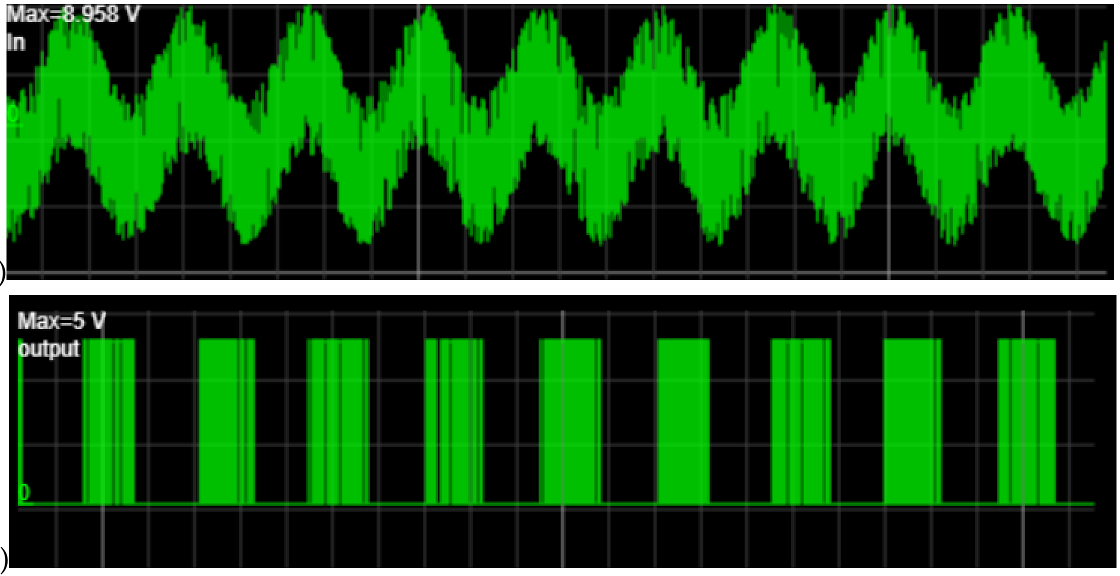
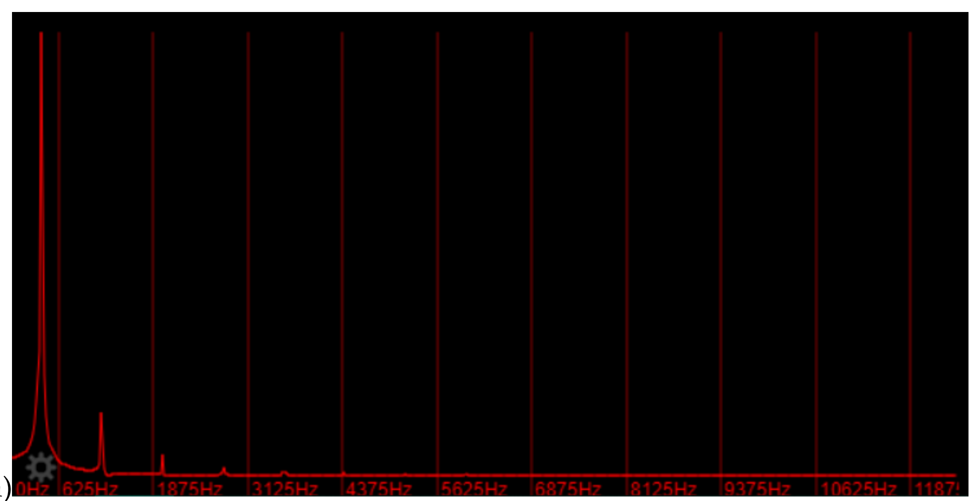
(c)
(d)


Figure 7. TDG of (a) input without noise (b) output without noise; (c) input with noise (d) output with noise

From Figure 7(b), it can be seen that the output is always 0V, but Figure 7(d) presents the output after adding a noise to the input. Combined with findings from Figure 6, this suggests that the output efficiency of the signal is enhanced by adding a noise, from zero output to an output showing some signal, but the output efficiency is not as good as the pulse wave.

<u>Triangular Wave:</u>

The MNV is 5.5V

(a)


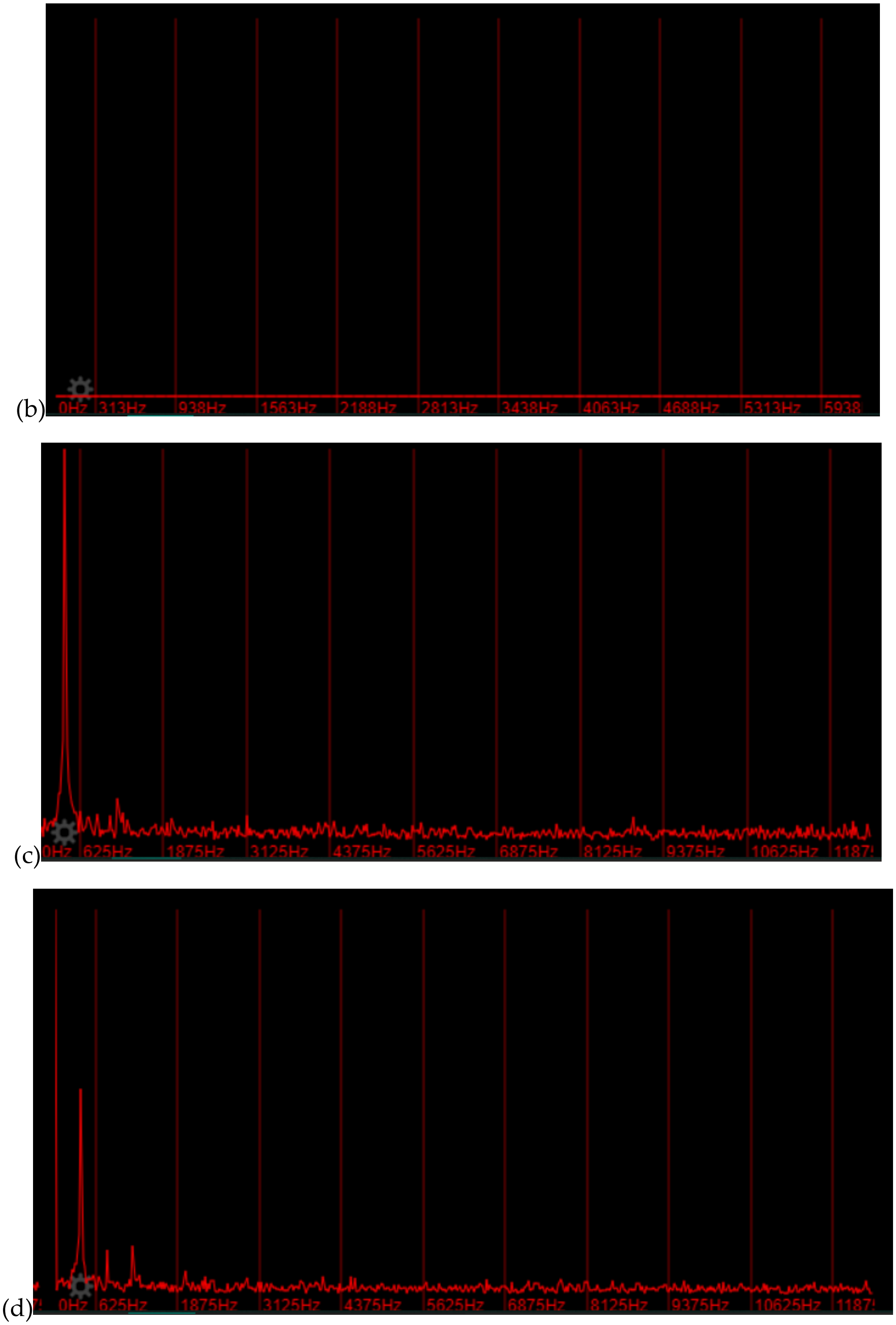


Figure 8. FDG of (a) input without noise (b) output without noise; (c) input with noise (d) output with noise

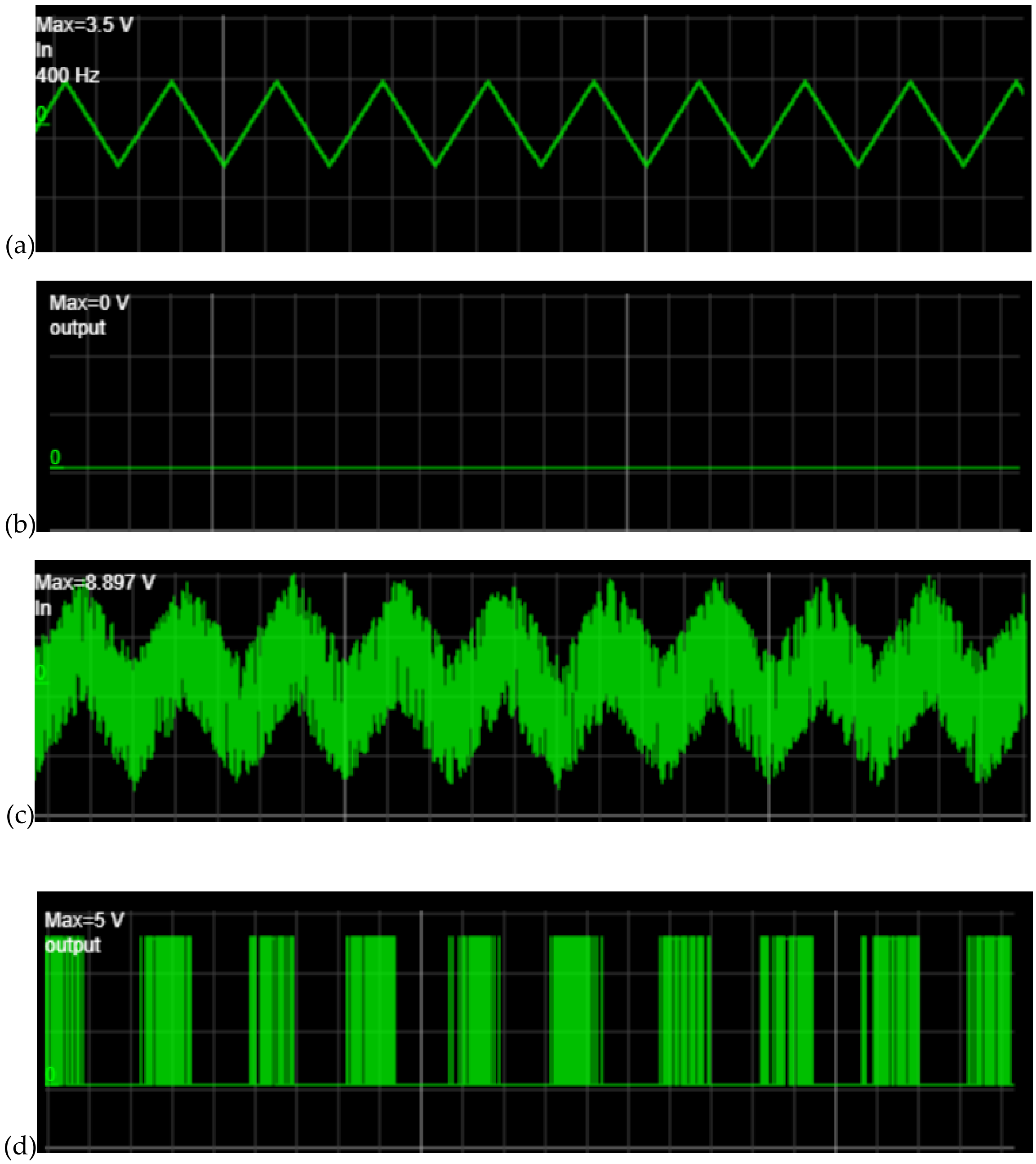
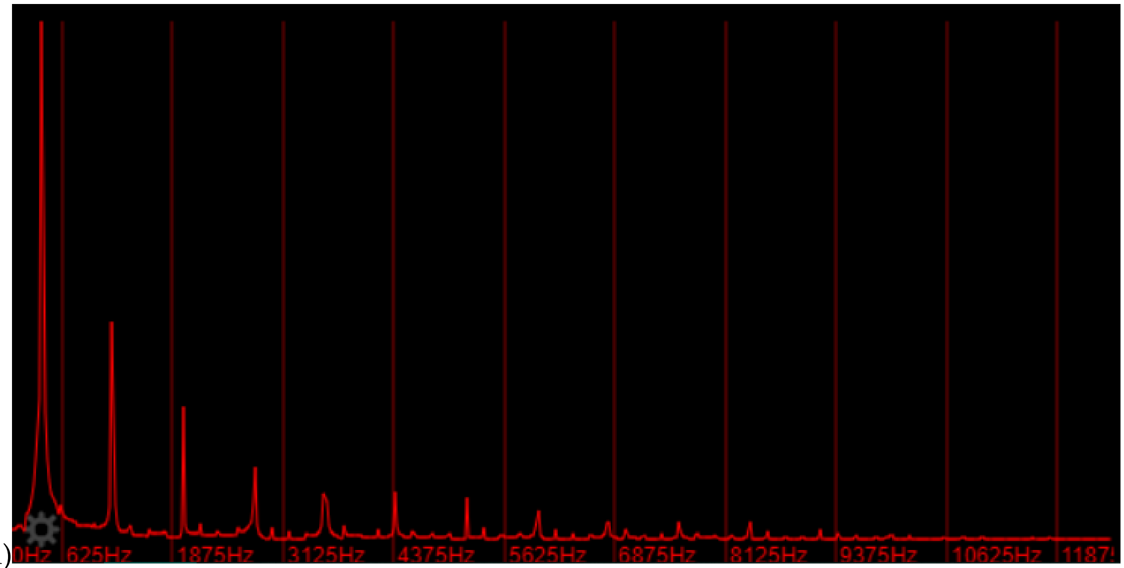


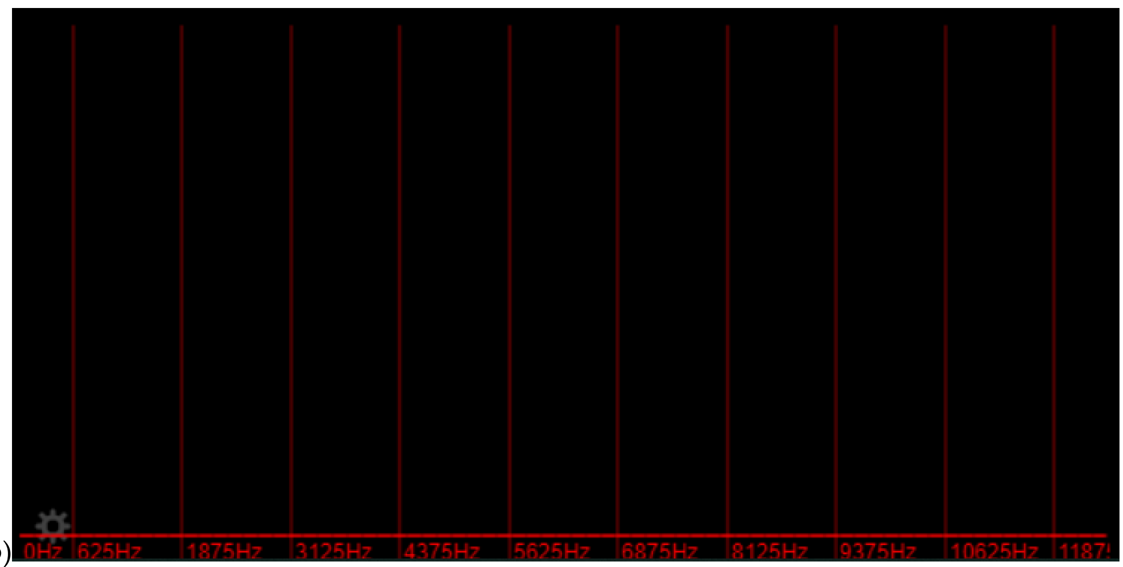
Figure 9. TDG of (a) input without noise (b) output without noise; (c) input with noise (d) output with noise

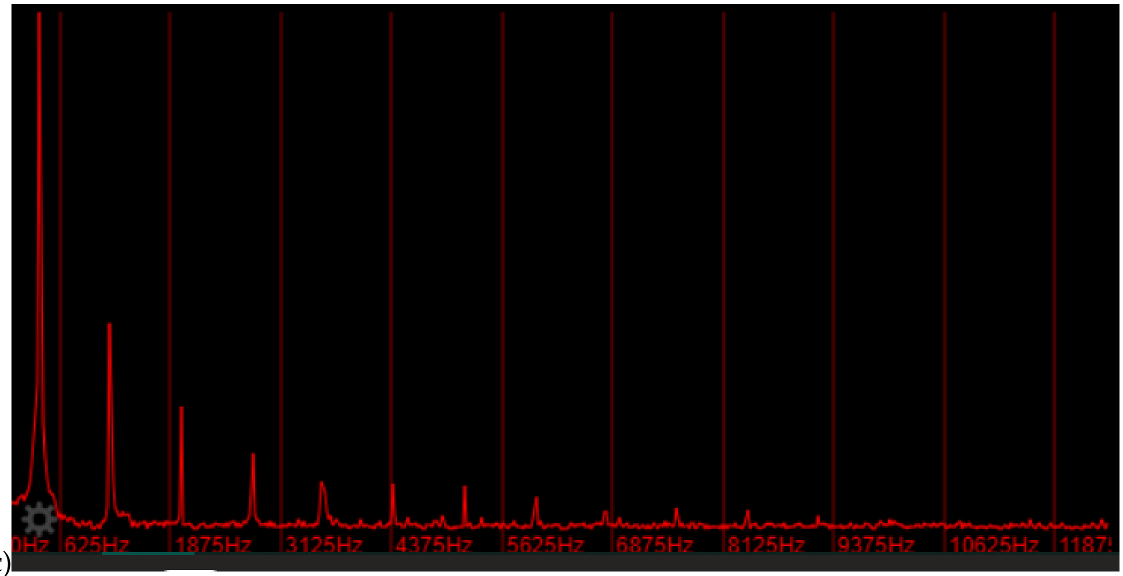
Figure 8 & 9 present graphs that are very similar with Figure 6 & 7. Although the original signals are different, but their input with noise and output are very similar. This can be viewed by comparing Figure 6(d) and 8(d), Figure 7(c) and 9(c).

<u>Square Wave:</u>

The MNV is 3V.

(a)

0Hz
625Hz
1875Hz
3125Hz
4375Hz
5625Hz
6875Hz
8125Hz
9375Hz
10625Hz

(b)

0Hz
625Hz
1875Hz
3125Hz
4375Hz
5625Hz
6875Hz
8125Hz
9375Hz
10625Hz

(c)


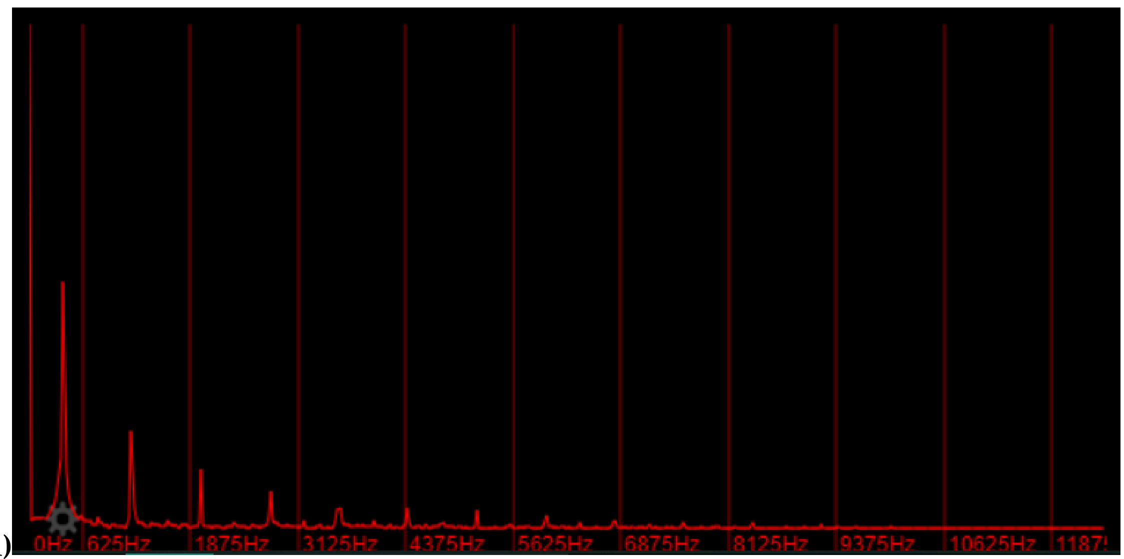
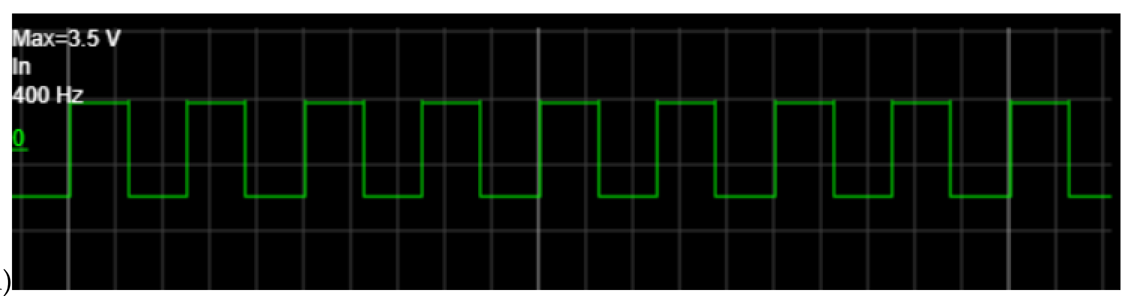
(d)


Figure 10. FDG of (a) input without noise (b) output without noise; (c) input with noise (d) output with noise

(a)


(b) (c) (d)

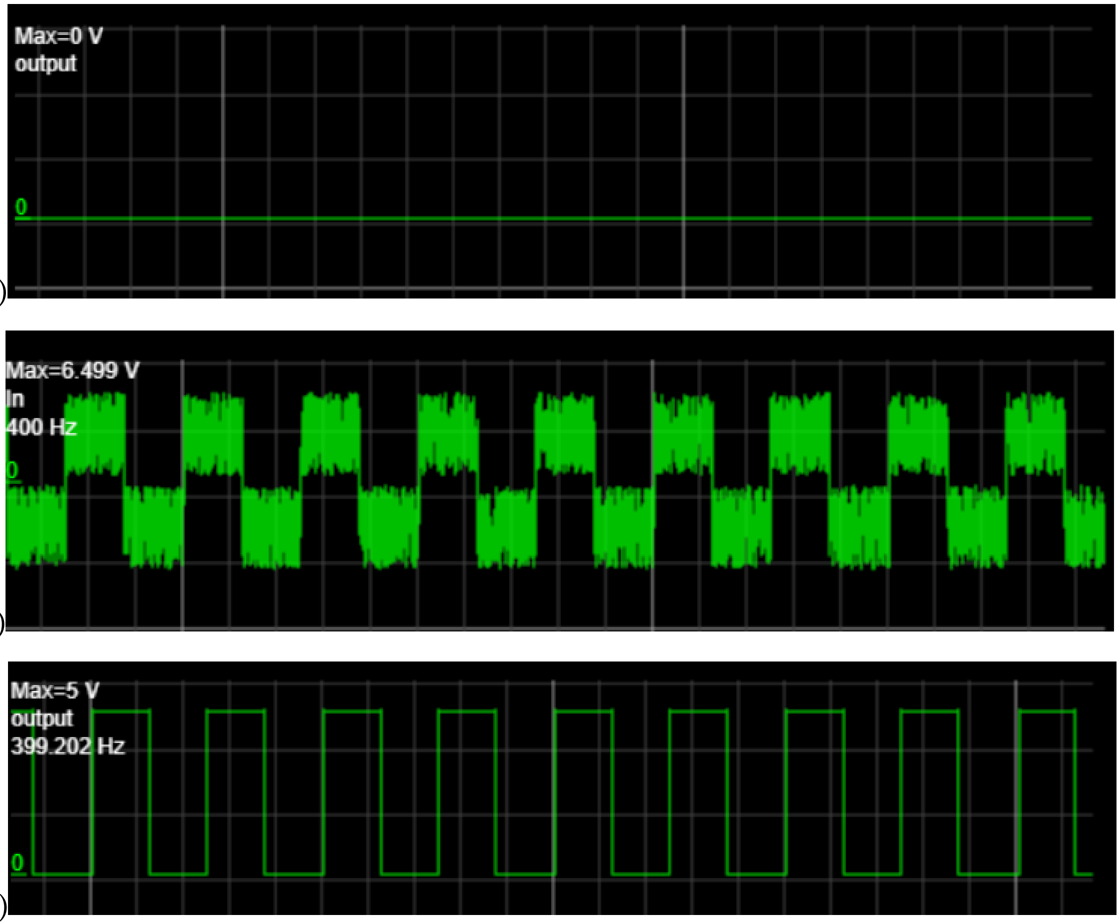
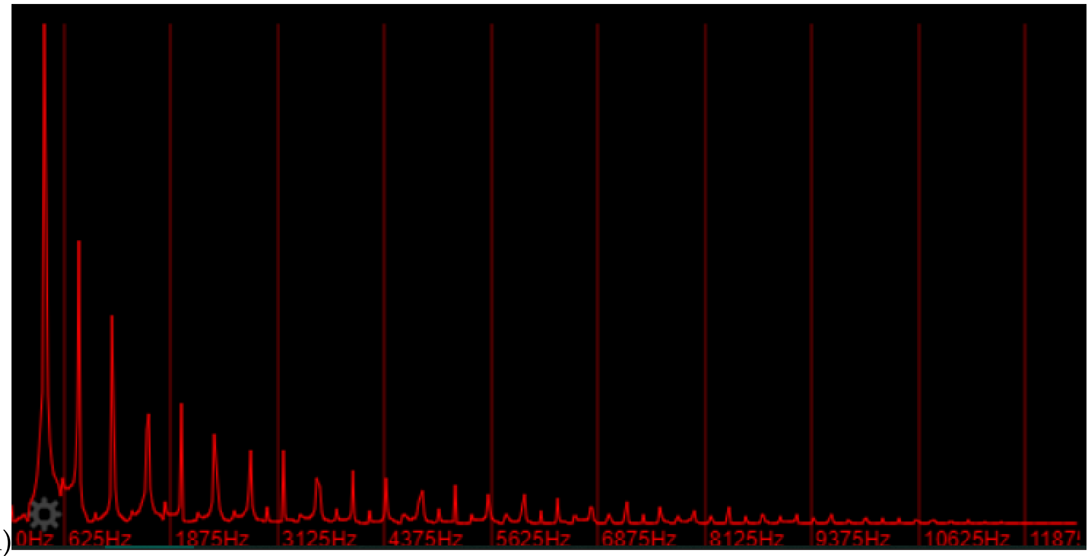


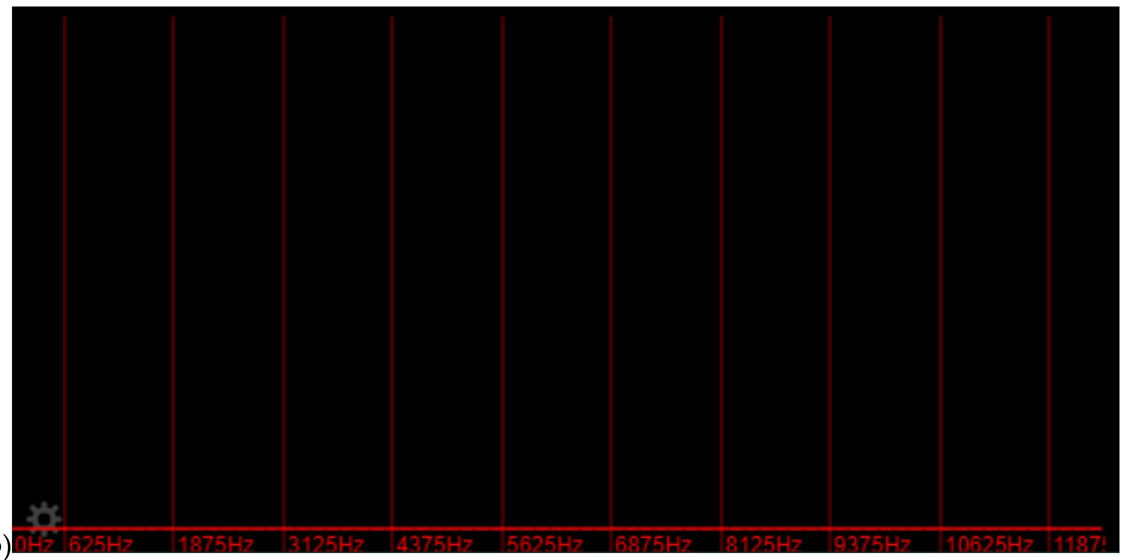
Figure 11. TDG of (a) input without noise (b) output without noise; (c) input with noise (d) output with noise

The result of the square wave is similar with pulse wave. For the square wave, the output with noise and the original signal have the same shape, but the difference is that the output is always non-negative, but the input is fluctuating between +MSV and -MSV.

<u>Sawtooth Wave:</u>

The MNV is 5.5V.


0Hz 625Hz 1875Hz 3125Hz 4375Hz 5625Hz 6875Hz 8125Hz 9375Hz 10625Hz
(a)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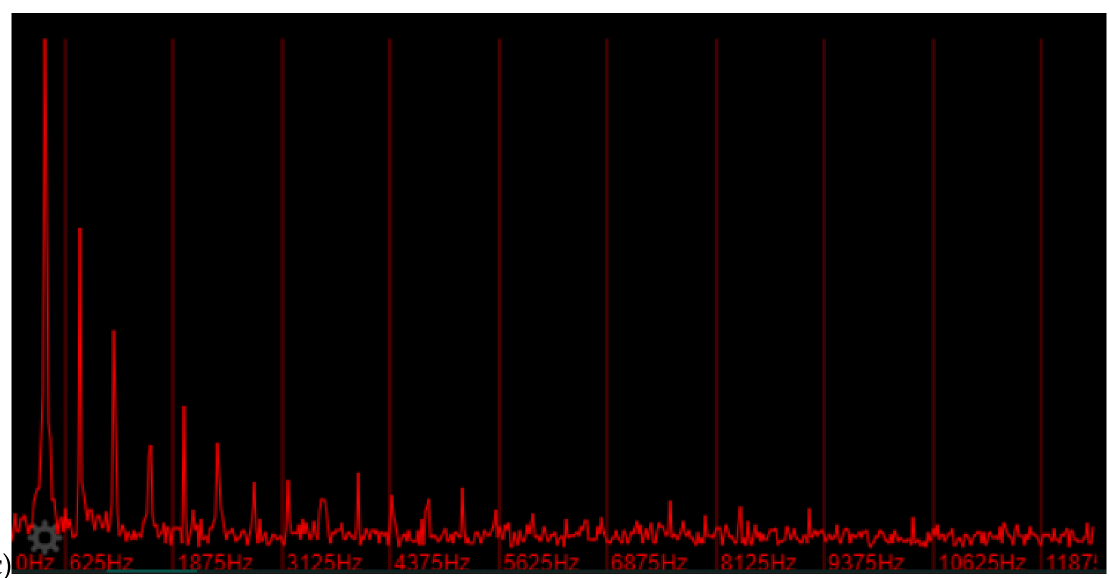
(b)


0Hz 625Hz 1875Hz 3125Hz 4375Hz 5625Hz 6875Hz 8125Hz 9375Hz 10625Hz
(c)

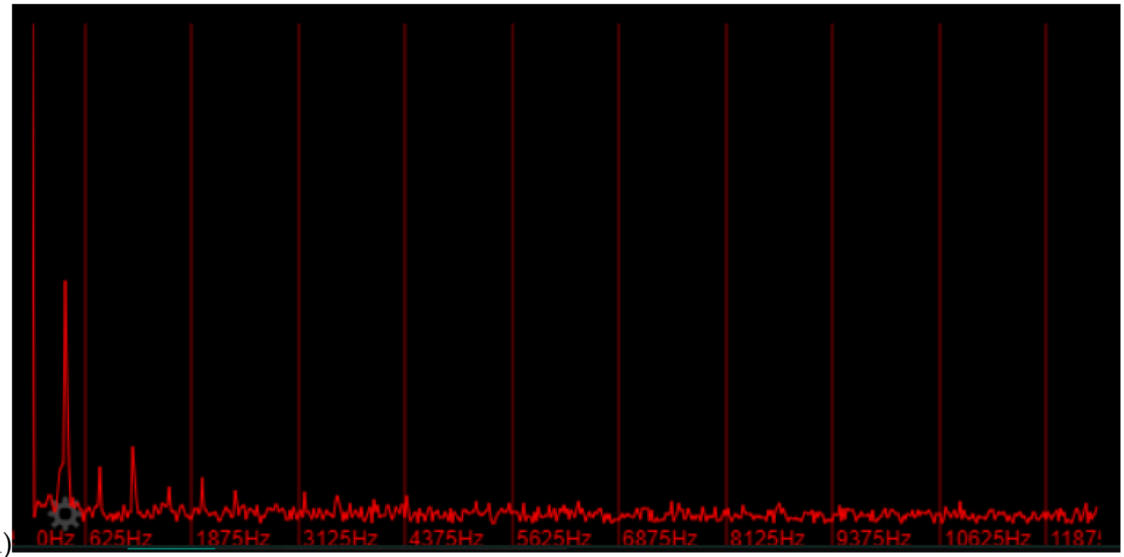
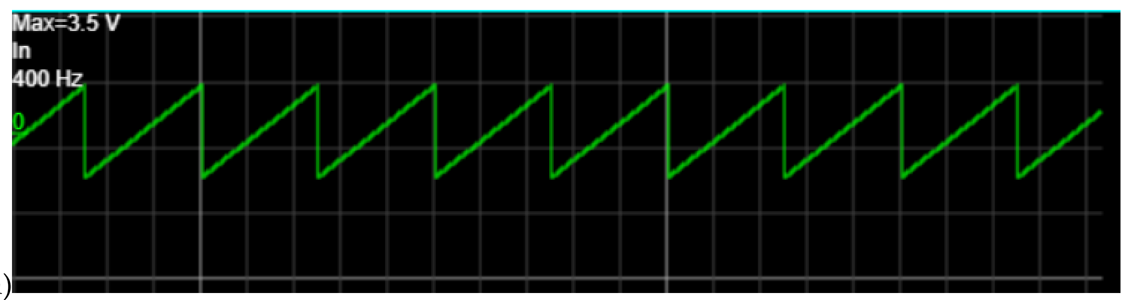
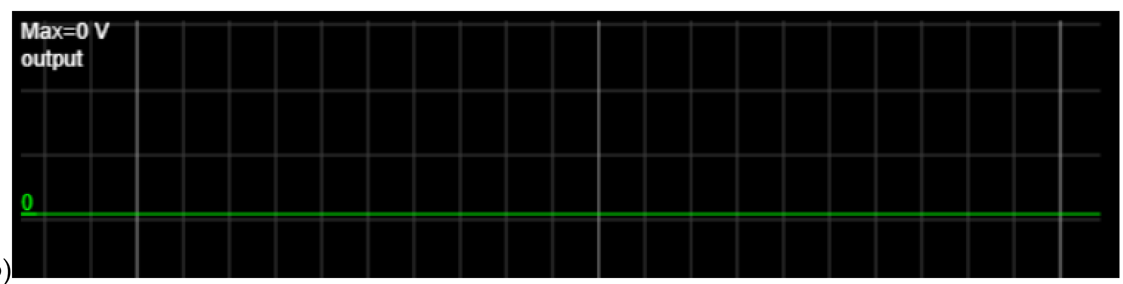
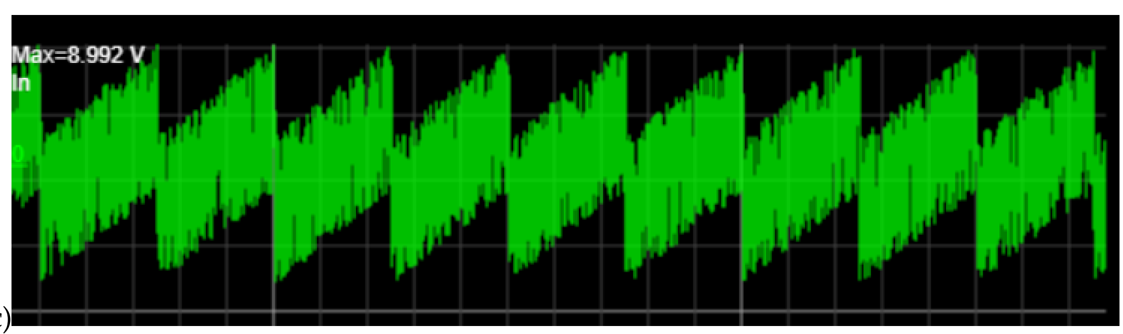
(d) 

Figure 12. FDG of (a) input without noise (b) output without noise; (c) input with noise (d) output with noise

(a) 

(b) 

(c) 

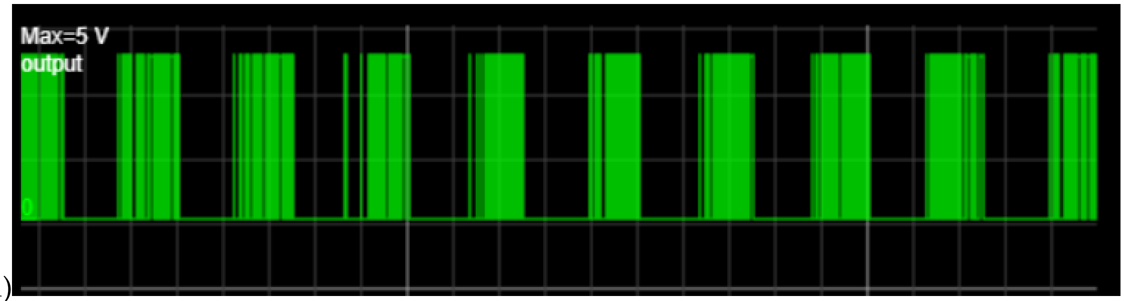
(d) 

Figure 13. TDG of (a) input without noise (b) output without noise; (c) input with noise (d) output with noise

By comparing Figure 12(a) and 12(d), the two spectrums are not similar. The peaks of low frequency are preserved, but the peaks of high frequency mostly disappeared.

3.2. Discussion and Inferences

Based on the above simulation, four key findings can be summarized as follows:

Finding 1: For the experiments of 5 types of signal source, the output waves when there is no noise in the input are zero, and the output waves when there is noise in the input are all non-zero.

Finding 2: By comparing the shapes of the input and output waves (noise) for triangular waves and sinusoidal waves, they look extremely similar.

Finding 3: Square waves (from voltage range from -MSV to +MSV) is converted to a pulse wave after stochastic resonance.

Finding 4: For pulse wave, the shape of its output wave with noise (after stochastic resonance) is identical with the signal input except the voltage magnitude is different.

Some of these findings such as Finding 2 & 4 directly address the research question since they are related to the output efficiency of the waves.

3.3. Conclusions

The digital signal waves (pulse wave and square wave) have the highest output efficiency since under certain circumstances the outputs are the exact same with the signal.

The high frequency components of the sawtooth waves did not pass the barrier efficiently. Its output efficiency is not high.

The triangular wave and sinusoidal wave have a similar output efficiencies. Their output efficiencies are lower than digital waves, but higher than the sawtooth wave.

4. Discussion and Synthesis

Finding 1 proves that stochastic resonance happens in all the experiments in this research, because it helps a signal that is originally incapable of passing the barrier to pass the barrier.

The significance of Finding 2 is that triangular waves can be similar with sinusoidal waves when a suitable amount of noise is added. Also, their signal-to-noise ratio after stochastic resonance is similar.

For Finding 3, the conversion from square wave to pulse wave can also be done by only a Schmitt trigger without a noise added, if the MSV of the square wave is higher than the upper limit of the Schmitt trigger. Thus, in this experiment, it can be concluded that although pulse wave and square waves have different voltage range (0 to MSV & -MSV to +MSV respectively), their behavior in stochastic resonance are similar. Their output efficiencies are also similar by comparing the graphs.

Finding 4 suggested that a pulse wave is a perfect type of wave that can show the highest SNR after stochastic resonance. For a square wave, the output signal after SR is also identical with the input signal, only that the voltage range has changed (shifted up), its shape is still the same.

The significance of this finding is that pulse waves are commonly used in electronics. If in special circumstances that noise is unavoidable, a Schmitt trigger might be installed to filter out the noise and leave the actual signal.

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Fauve, S. & Heslot, F. (1983) Stochastic Resonance in A Bistable System. *Physics Letters, 97A(1,2), 5-7*

Benzi, R., Parisi, G., Sutera, A. & Vulpiani, A. (1982) Stochastic Resonance in Climate Change. *Tellus* 34(1), 10-16

Benzi, R., Sutera, A. & Vulpiani, A. (1981) The Mechanism of Stochastic Resonance. *Journal of Physics A: Mathematical and General* 14(11)