

# Automated Fire Extinguishment using Low-Frequency Sound Waves

Santhiya V, Swetha V, S Tamil Nilavan  
UG Scholars, Department of Electronics and  
Communication Engineering  
Sri Venkateswara College of Engineering (Autonomous)  
Chennai, India

M K Varadarajan, S Kalyani  
Assistant Professors, Department of Electronics and  
Communication Engineering  
Sri Venkateswara College of Engineering (Autonomous)  
Chennai, India

**Abstract** - Conventional fire suppression systems rely on water, chemical agents, foam, or carbon dioxide to extinguish flames. While these techniques are effective, they frequently cause secondary damage to sensitive electronic equipment, introduce chemical residues, or pose safety risks in confined environments. This research presents a novel and eco-friendly fire suppression approach using low-frequency acoustic waves generated through digital signal synthesis techniques. The proposed system employs an Arduino-based Direct Digital Synthesis (DDS) architecture to generate stable low-frequency sinusoidal signals in the range of 30–60 Hz. The digital waveform is converted into an analog signal using Pulse Width Modulation (PWM) followed by an RC low-pass filter for waveform reconstruction. The filtered signal is amplified using a pre-amplifier and high-power audio amplifier to drive a 10-inch subwoofer capable of generating high-energy acoustic pressure waves. A directional collimator is used to focus the acoustic energy toward the flame region, thereby increasing sound pressure density and improving suppression efficiency. Experimental results demonstrate that acoustic frequencies near 41 Hz produce significant airflow disturbances that disrupt the combustion process by altering oxygen concentration and destabilizing the flame front. Small-scale flames were successfully extinguished within 3–5 seconds without the use of chemical agents. The proposed acoustic suppression method provides a sustainable, residue-free, and reusable fire suppression mechanism suitable for laboratories, electronic equipment facilities, and industrial safety applications.

**Keywords:** Acoustic Fire Suppression, Direct Digital Synthesis, Digital Signal Processing, Pulse Width Modulation, Low-Frequency Acoustics, Embedded Signal Generation.

## I. INTRODUCTION

Fire hazards pose a significant threat to human safety, infrastructure, and industrial systems. Traditional fire suppression methods are primarily designed to eliminate one of the four components of the fire tetrahedron: heat, oxygen, fuel, or the chemical chain reaction sustaining combustion. Common extinguishing agents include water, foam, dry chemical powders, and carbon dioxide. Although effective in many scenarios, conventional suppression systems suffer from

several limitations. Water cannot be safely used in electrical environments, chemical powders leave corrosive residues that damage electronic equipment, and carbon dioxide extinguishers pose potential respiratory hazards in confined spaces. These limitations motivate the development of alternative suppression techniques that are environmentally safe and non-destructive.

Acoustic fire suppression has emerged as a promising research area in which sound waves are used to disturb the combustion process. Sound propagates through air as pressure oscillations consisting of alternating compression and rarefaction cycles. When sufficiently intense acoustic waves interact with a flame, they generate periodic airflow disturbances that alter the oxygen supply and disrupt the stability of the flame front.

Previous research indicates that low-frequency acoustic waves between 30 Hz and 60 Hz are particularly effective for flame suppression due to their high air displacement and pressure amplitude. These frequencies produce significant oscillatory airflow that interferes with fuel-oxygen mixing near the combustion zone.

This work proposes a digital signal processing-based acoustic fire suppression system that generates precisely controlled low-frequency signals using Direct Digital Synthesis implemented on an Arduino microcontroller. The generated waveform is amplified and delivered through a subwoofer-collimator acoustic system to create a focused pressure field capable of extinguishing flames without chemical agents.

## II. BACKGROUND AND RELATED WORK

Fire suppression techniques traditionally rely on four primary mechanisms:

1. Cooling
2. Oxygen removal (smothering)
3. Fuel isolation
4. Chemical inhibition of combustion reactions

Water-based extinguishers operate through cooling, absorbing heat energy from the combustion zone. Foam suppressors isolate oxygen from the flame surface. Dry chemical extinguishers interrupt the combustion chain reaction using compounds such as mono-ammonium phosphate or sodium bicarbonate.

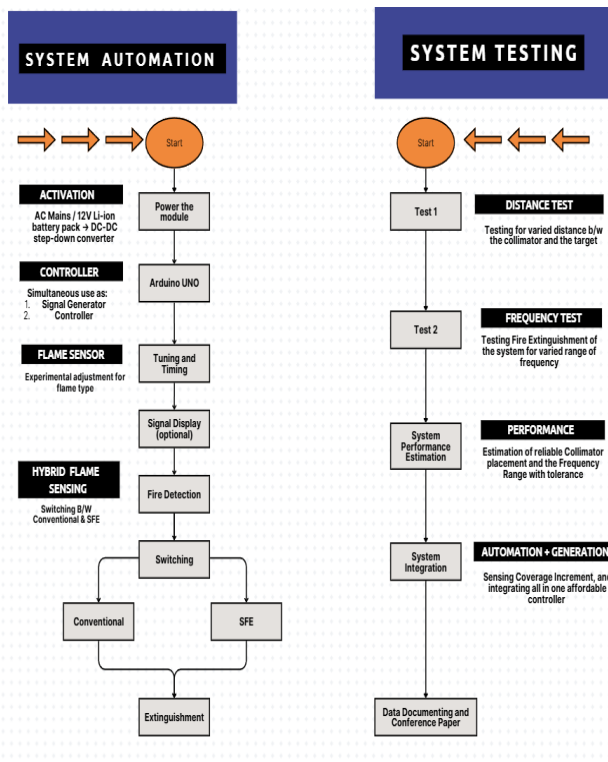
However, these techniques introduce significant drawbacks including corrosion, residue deposition, environmental contamination, and damage to sensitive equipment.

Recent research has explored acoustic suppression techniques as a chemical-free alternative. Studies demonstrate that sound waves can interact with flames through three primary mechanisms:

1. **Oxygen displacement** caused by oscillatory airflow & pressure variation
2. **Cooling effects** due to pressure variations in the combustion zone
3. **Flame detachment** when acoustic airflow velocity exceeds flame propagation velocity

Experimental research indicates that low-frequency sound waves provide the highest suppression efficiency because they produce stronger air displacement and pressure oscillations compared to high-frequency acoustic waves.

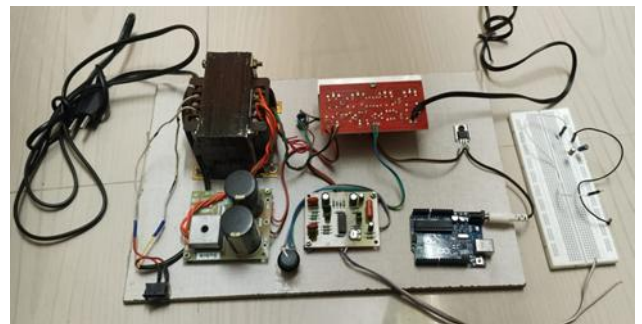
### III. SYSTEM ARCHITECTURE



The proposed system consists of four major subsystems:

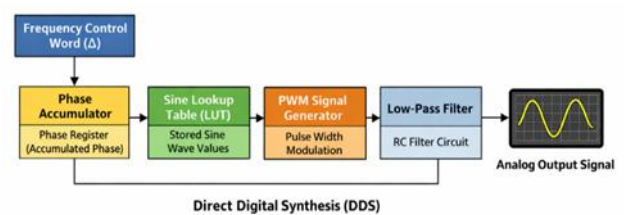
1. Digital Signal Generation Unit
2. Signal Conditioning and Filtering Unit
3. Power Amplification Unit
4. Acoustic Projection and Focusing Unit

The digital signal generation stage produces low-frequency sinusoidal waveforms using Direct Digital Synthesis implemented on an Arduino Uno microcontroller. The PWM output is converted into an analog signal through an RC low-pass filter. The reconstructed analog signal is amplified using a pre-amplifier and high-power audio amplifier before being transmitted to a subwoofer speaker. A collimator structure focuses the acoustic energy toward the target flame.

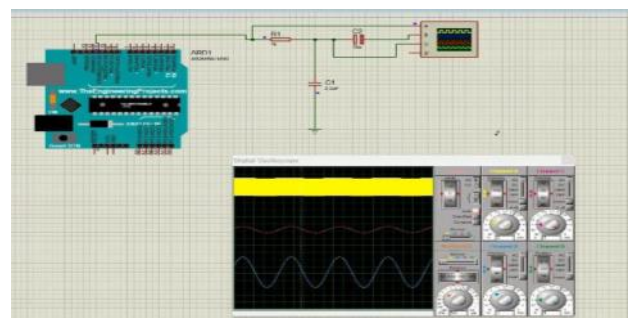


### IV. Digital Signal Generation Using Direct Digital Synthesis

Direct Digital Synthesis (DDS) is a signal generation technique commonly used in digital signal processing for generating stable and frequency-accurate waveforms. DDS operates by incrementally advancing a



phase accumulator that indexes a lookup table containing sampled sine wave values.



The output frequency is given by:

$$\Delta = \frac{f_{out} \times N}{f_{sample}}$$

$f_{out}$  = output frequency

$f_{sample}$  = sampling frequency

$N$  = number of samples in lookup table

$\Delta$  = phase increment value

Sampling frequency = 20 kHz

Lookup table size = 200 samples

Desired output frequency = 41 Hz

The phase increment becomes, At each sampling interval, the phase accumulator increases by  $\Delta$

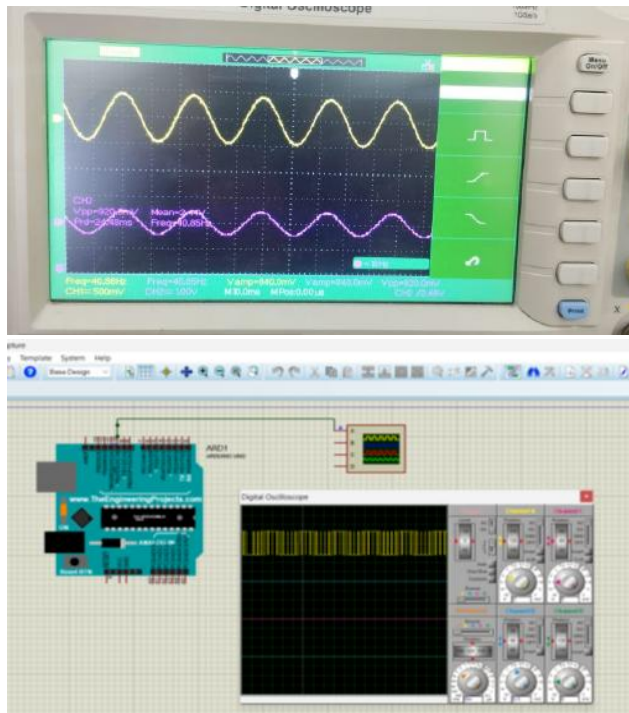
$$\Delta = \frac{41 \times 200}{20000} = 0.41$$

### V. PWM-Based Digital-To-Analog Conversion

The DDS output is a digital representation of a sine wave. This signal is converted into an analogue waveform via pulse-width modulation.

The PWM signal operates at approximately **62 kHz**, significantly higher than the target signal frequency. Each PWM duty cycle represents the instantaneous amplitude of the sine waveform. To reconstruct the analog waveform, the PWM signal is passed through an RC low-pass filter.

$$f_{pwm} = 62 \text{ kHz}$$



### VI. RC Low-Pass Filter Design

The cutoff frequency of the RC filter is given by

$$f_c = \frac{1}{2\pi RC}$$

For the designed filter:

$R = 1 \text{ k}\Omega$

$C = 2.2 \text{ }\mu\text{F}$

$$f_c \approx 72.3 \text{ Hz}$$

This cutoff frequency allows the **41 Hz** fundamental signal to pass while attenuating high-frequency PWM components.

### VII. Acoustic Power Amplification

The filtered signal is first fed into a subwoofer pre-amplifier for signal conditioning and gain control. The output is then amplified using a **4-FET** mono power amplifier capable of delivering 150–300 W of output power. This amplification stage ensures sufficient acoustic pressure generation to influence flame behaviour.

### VIII. Acoustic Emission And Collimator Design

The amplified signal drives a 10-inch subwoofer speaker, which converts electrical signals into acoustic pressure waves. To maximize suppression efficiency, a collimator structure is mounted in front of the speaker.

The collimator performs the following functions:

1. Focuses acoustic energy toward the flame
2. Reduces sound dispersion
3. Increases acoustic pressure density

This directional sound propagation improves interaction between the acoustic field and the combustion zone.

### IX. Experimental Methodology

The experimental setup consisted of the following components:

1. Arduino DDS signal generator
2. RC low-pass filter
3. Subwoofer pre-amplifier
4. Power amplifier
5. 10-inch subwoofer
6. Acoustic collimator

Controlled flame sources such as candles and alcohol burners were placed at a distance of **10–15 cm** from the acoustic source. The acoustic frequency was varied between **30 Hz and 60 Hz** to identify the optimal suppression range.

## X. SYSTEM TESTING AND PERFORMANCE ESTIMATION

### 1. Distance test

Distance (CM)	Time (Seconds)
40	1
50	1.23
60	1.88
70	2.60
80	5.18

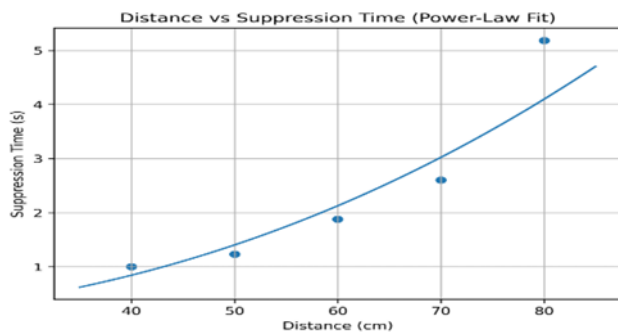
The experimental results demonstrate a direct relationship between distance and suppression time, indicating that the system's effectiveness decreases with increasing distance.

The experimental data shows a nonlinear increase in suppression time with distance. When the distance is doubled from 40 cm to 80 cm, the suppression time increases by approximately five times, indicating a power-law relationship. This behavior deviates from linear proportionality and is attributed to rapid decay in acoustic pressure and energy dispersion.

Therefore, the suppression time can be formulated as:

$$T(r) = kr^n, n \approx 2$$

$K$  = System Constant  
 $T$  = Suppression Time  
 $R$  = Distance



### 2. Frequency test

Frequency (Hz)	Time (Sec)	Syst. Performance
35	< 1	Comparable to optimal condition
41	<= 1	Maximum suppression efficiency
47	~ 2	Moderate suppression
65	~ 14	Delayed suppression
70	~ 20	No observable suppression

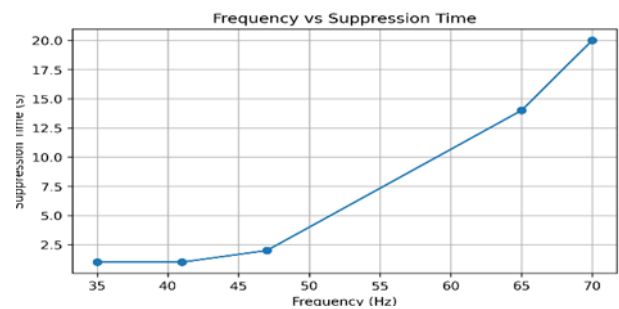
The suppression mechanism is governed by the interaction between acoustic pressure waves and the flame structure. Low-frequency sound waves (35–45 Hz) generate significant

pressure oscillations and volumetric air displacement, which disrupt the stability of the air–fuel mixture and reduce oxygen availability at the flame front.

As the frequency increases, the amplitude of air displacement decreases, resulting in reduced perturbation of the combustion zone. Consequently, the effectiveness of flame suppression diminishes at higher frequencies.

$$T(f) = e^{0.11(f-41)}$$

$T$  = Suppression Time  
 $f$  = operating Frequency



## XI. RESULTS AND DISCUSSION

Simulation using Proteus verified the correctness of PWM waveform generation and filtering. MATLAB Simulink simulations were used to evaluate the amplifier stage and estimate acoustic power output. Hardware testing confirmed stable signal generation at approximately **40.8 Hz**, closely matching the designed frequency. When the acoustic system was activated, oscillating pressure waves caused visible disturbances in the flame structure. The oscillatory airflow altered the fuel-oxygen mixing process and destabilized the combustion zone.

1. Significant flame deformation under acoustic exposure
2. Reduction in flame height and intensity
3. Complete flame extinction within less than **5 seconds**

These results confirm that low-frequency acoustic waves can effectively suppress small flames without chemical agents.

## XII. FUTURE WORK

1. Development of portable acoustic fire suppression devices
2. Integration of Hybrid fire detection systems using conventional methods through automation with sensors.
3. Adaptive frequency control based on flame dynamics
4. Implementation of multi-speaker acoustic arrays for large fire suppression

Such advancements could enable practical deployment of acoustic suppression technology in industrial safety systems.

### XIII. CONCLUSION

This research demonstrates the feasibility of an acoustic fire suppression system based on digitally synthesized low-frequency sound waves. By combining Direct Digital Synthesis, PWM-based digital-to-analog conversion, signal filtering, and high-power acoustic amplification, the system generates pressure waves capable of disrupting the combustion process. Experimental results confirm that controlled low-frequency acoustic waves can extinguish small flames rapidly while eliminating the environmental and equipment damage associated with traditional fire suppression methods.

The integration of digital signal processing techniques with acoustic field engineering highlights the potential of **signal-driven fire suppression technologies** as a sustainable and non-destructive alternative for future fire safety systems.

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