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Optimization of Drone Sound Quality based on Active Noise Control Method

Department of Mechanical and Automotive Engineering

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Shen Yu

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Supervisor: Prof. Chang-Myung Lee

Author: Shen Yu

Department of Mechanical and Automotive Engineering
University of Ulsan

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Approved by

Professor Chang-Myung Lee

Shen Yu 의 공학박사학위 논문을 인준함

심사위원장 이병룡 (인)

심사위원 김도중 (인)

심사위원 이장명 (인)

울산대학교 대학원

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ABSTRACT

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SHEN　YU

Department of Mechanical and Automotive Engineering

In recent years, with active research on batteries and autonomous aviation technologies, attempts have been made to replace traditional fuel aircraft with All-Electric Aircraft(AEA) while eliminating direct carbon dioxide and non-carbon dioxide warming and reducing aviation pollution to the atmospheric environment. But with the widespread use of drones, their noise problems are increasing. For example, many drones are used in transportation, media, and agriculture, which inevitably causes prolonged noise exposure, becoming a major environmental sanitation problem.

Great efforts have been made on drone noise reduction levels over the past few decades. Passive noise reduction by optimizing the shape of drone propeller blades is currently the most widely used method. However, it may affect the aerodynamic performance of the propeller, thus requiring a trade-off on noise reduction and endurance performance. With the method of noise reduction technology, the Sound Pressure Level (SPL) is not the only criterion to judge the noise reduction level. The Sound Quality(SQ) is becoming more and more widely studied and used. Therefore, according to the noise characteristics of drone, this paper combines the traditional noise active control adaptive LMS algorithm and psychoacoustic parameters, proposes the Active Sound Quality Control （ASQC) using the LMS algorithm to eliminate the noise frequency band with the most significant impact on the psychoacoustic parameters, to achieve the purpose of improving the noise quality of drone.

First, this paper introduces the noise characteristics of drones and the commonly used noise reduction methods and analyzes the advantages and disadvantages of various noise reduction schemes. Then, the overall design scheme of ASQC has developed with drone noise characteristics Active Noise Control(ANC) theory and the theory of active noise control system. Considering the algorithmic computational complexity and hardware requirements, a scheme for using single-frequency audio as a secondary noise is proposed, which simplifies the complexity of the entire system while effectively improving the sound quality.

Then, drone noise collection and analysis experiments were performed in the silencing chamber. Accurate drone noise data are used to make the simulation results close to the actual situation. Considering that the sound quality is often strongly correlated with human subjective feelings, the calculated psychoacoustic parameters and the subjective evaluation results are used for regression analysis to obtain the evaluation formula of drone sound quality. In conducting the subjective evaluation, the Noise Improvement Level(NIL) is introduced, which intuitively reflects the degree of raw quality improvement of the audio processed by the ASQC system compared to the original noise data.

Finally, the obtained drone sound quality evaluation formula is reintroduced to form the complete ASQC system. Processing using a new set of drone noise data, which compared with subjective evaluation results, yielded good results.

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ABBREVIATIONS

AEA	All-Electric Aircraft
SPL	Sound Pressure Level
ANC	Active Noise Control
ASQC	Active Sound Quality Control
NIL	Noise Improvement Level
MAV	Micro Air Vehicles
SUAV	Miniature UAV or Small
UAM	Urban Air Mobility
NIOSH	National Institutes for Occupational Safety and Health
FFT	Fast Fourier Transform
LMS	Least Mean Squares
FXLMS	Filtered-X Least Mean Squares
SI	System Identification
SQM	Sound Quality Metric
IL	Improvement Level

1.INTRODUCTION

1.1 Research Background

1.1.1 The History of the Development of the Drone

Multi-rotor type unmanned aircraft vehicles (UAV) are being widely studied and applied, commonly referred to as drones. This is a crewless aircraft operated using radio remote control equipment and self-contained program control devices and can be operated remotely by humans. A complete unmanned flight system (UAS) also includes a ground controller and a communication system[1, 2].

Initially originating in the early 20th century, drones were developed for military reconnaissance, surveillance, and shooting training[3]. In 1917, Peter Cooper and Elmer A.Sperry invented the first autonomous gyro stabilizer, which allows the aircraft to maintain a balanced forward flight, and unmanned aircraft vehicles were born. It can fly 50 miles with 300-pound bombs but was never applied to actual combat. In 1935, the invention of the DH.82B Queen Bee marked that the drone could fly back to the take-off point for reuse. During World War II, more drones emerged, such as the Argus As 292 and JB-4. However, they still belong to remote-controlled aircraft, not drones in the array sense. So far, more and more countries have begun to increase the military use[4, 5] of drones and gradually use drones[6] instead of traditional aircraft.

1.1.2 Public Health Issues from Drones Noise

Compared with military drones, although the development of civilian drones is relatively late, the development speed is very rapid[7]. At present, more than 70% of the market share is occupied by DJI (C.N.), followed by Yuneec (C.N.), 3D Robotic (USA), and parrot (F.R.)[8]. As of May 2021, the Federal Aviation Administration has registered 873,573 drones, of which 42% are commercial drones, and 58%[9] are civilian drones. At the same time, the global drone market in 2021 will reach 214.7 billion U.S. dollars[10]. Compared with 2020, the growth will exceed 100%.

While the drone market is growing, drone use has created many social problems related to privacy, safety, and noise. Most of the security and privacy problems can be solved by setting up the no-fly zone and the drone registration system[11], but the drone noise problem has not been fully addressed.

Because the noise characteristics of drones are very different from traditional aircraft, research is needed to distinguish between drones and traditional aircraft. In 2018, NASA convened noise experts from various industries to form an Urban Air Mobility (UAM) Noise Working Group, designed to address noise issues associated with urban air traffic, including drones[12]. A psychoacoustic subjective evaluation test of 38 by Andrew et al[13]. found that drone noise was more likely to bother than road vehicle noise. In further, Torija, by calculating the psychoacoustic index, found that the drone has higher loudness, sharpness[14]. However, subjective tests are still needed to determine the results because the current psychoacoustic evaluation system is not perfect enough.

1.2 Review of Noise Research

1.2.1 Traditional Noise Evaluation

Noise is the sound we do not want that destroys human physiological and psychological health. A high level of noise can cause symptoms such as hearing loss, hypertension, ischemic heart disease, sleep disorders, and other health hazards[15]. Prolonged exposure to a low level of noise can also lead to significant discomfort in the body[16]. There is also a significant causal relationship between noise and physiological health, and unpleasant sounds can cause significant changes in human psychology[15].

In traditional noise studies, A-weighted or ITU-R 468 weighted Sound Pressure Level(SPL) is usually used as a unique indicator to measure and evaluate the noise[17]. Environmental noise usually refers to the accumulation of all noise in a particular environment, and Figure.1 illustrates the familiar sources of environmental noise in centralized daily life.

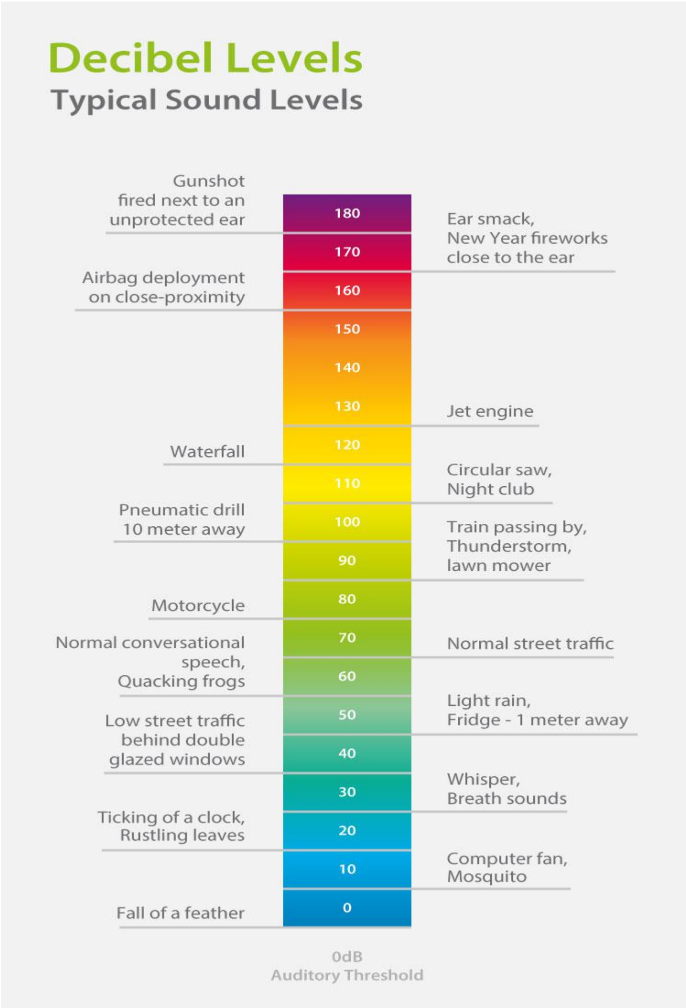


Fig. 1 Tpical Sound Levels of common noise sources

Some specific regions or occupations are faced with the risk of continuous exposure to high levels of noise. For this reason, many countries and regions have successively issued laws and regulations on noise control: the European Environment Agency has issued relevant regulations to monitor and control noise[18, 19]; the National Institutes for Occupational Safety and Health (NIOSH) also put forward relevant suggestions and recommended standards for workplace noise standards[20, 21]; in addition, the EU issued Marine Strategy Framework Directive (MSFD), underwater noise is also included in the scope of regulation[22].

Recent research indicates that the traditional A-weighted SPL as the only index for evaluating noise is incomplete. The reason is that it does not represent the quality characteristics of a sound and, in other words, this indicator does not fully respond to human subjective feelings of sound. In fact, human sensitivity to sound at different frequencies, so two sounds with the same SPL may bring different auditory perceptions. Therefore, we cannot reduce the SPL as the sole goal of improving the acoustic environment.

1.2.2 Development of Sound Quality Research

For the earliest concept of sound quality dating back to 1883, Stumpf proposed the concept of 'sound characteristics' to explain the phenomenon that two sounds have the same SPL and give different subjective perceptions. In the 1980s, it was found that some vehicles had higher A-weighted SPL but sounded comfortable[23]. More and more people have devoted themselves to research this phenomenon, and many new indices have been created to evaluate the human subjective perception of noise. Blauert and Bodden first proposed the concept of sound quality in 1994[24]. In their research, the concept of 'sound' refers to the physical process of sound wave formation and includes the process of human auditory perception. "Quality" refers to the subjective judgment made by human beings on sound in the process of perception, which emphasizes more on subjectivity.

The establishment of the concept of sound quality has brought new challenges to modern noise research because it is related to acoustic properties and the human mental state. As people's s auditory preferences change, sound quality will become a real-time variable, so sound quality is still necessary to constantly improve the concept.

1.3 Sound Quality Evaluation Method

1.3.1 Fundamental Principles

Compared with the traditional environmental noise research, the research on noise and sound quality has extreme subjectivity and cross-cutting. Its testing method, experimental scheme, and data processing analysis method are unique. Sound Quality Evaluation(SQE) steps are designed to use human auditory perception in decomposing a sound into a handful of parameters upon which the judgment of pleasantness is made or to approximate these abilities with empirical equations.

Generally, SQE is a complex process containing three kinds of knowledge: (1) acoustics (the physical parameters or acoustic factors), (2) psychoacoustics (the relationship between human auditory perception and physical parameters), and (3) psychology (subjective perception). According to international practice, the SQE method can be mainly divided into subjective and objective evaluation. Subjective evaluation of sound quality is how people understand noise sound quality from the perspective of subjective perception; objective evaluation of sound quality is to seek psychoacoustic and physical acoustic properties of noise sound quality.

1.3.2 Objective Evaluation and Sound Quality Metrics

The purpose of the objective SQE is to establish the connection between the subjective perception of SQ and physical acoustics and psychoacoustics. Some acoustic metrics were developed to illustrate human responses and preferences to different sounds in objective psychoacoustic studies. These metrics, derived from psychological response mechanisms and auditory perceptions of human beings, are called (SQMs). Among the existing SQMs, some studies have defined relatively perfect parts of them, but very few have international standards.

The current international research is mainly aimed at the specific noise environment, and the research methods and results will be very different for different application scenarios. For different application scenarios, the objective evaluation needs to combine the spectral characteristics of noise, physical acoustic parameter, psychoacoustic parameter, and other aspects and use the analysis of variance, correlation analysis, and multiple linear regression. Famous companies in the acoustic fields of AVL LIST[25], B & K company[26], and HEAD acoustic[27] have all used different SQMs to build their own SQE systems.

The following are the remarkable achievements of the objective SQE research：

- In 1956, Robinson and Dadson[28] defined the equal-loudness for pure sounds in free-field conditions, setting the foundation for subsequent studies on the loudness of SQMs. Based on this, Zwicker[29, 30] proposed the loudness models for variable sounds, and its model is accepted as an international standard[31].
- Some researchers have described the subjective characteristics of sound quality based on several psychological characteristics. In 1994, Hussain[32] proposed the annoyance index. Aures combined loudness, roughness, sharpness, and tone to propose the notion of annoyance index. Castellengo[33] proposed ways to specify human auditory perception with tone, brightness, sensory euphony, and timbre.
- In 1999, based on a lot of subjective evaluation experiments and analysis, Scott and Jeff[34] proposed a model for evaluating vehicle noise based on the fluctuation, loudness, and standard deviation of loudness in

the time domain. In the same year, Hoeldrich[35] and Pflueger[36] proposed an improved model for researching the roughness calculation of vehicle interior noise.

- Low-frequency noise has a significant impact on sound quality[37, 38]. In 2000， Hashimoto[39], in the research of the sound quality on vehicle interior noise, the sound pressure feeling generated by the low- frequency noise below 300Hz was called the roar feeling. The model results of psychoacoustic Booming Level driving in steady-state are well correlated with roar sensation. During the acceleration, the Booming index is proposed to evaluate the external noise at the idle speed and the engine acceleration at a low rotational speed.
- In 2002, C.Hogstrom[40] researched the annoyance level of noise caused by trains' air conditioning and ventilation system by analyzing its spectral components and psychological parameters. Based on the analysis of the modulated model, it is found that sharpness and modulation are the key factors affecting annoyance level and the key to improving sound quality. The estimated model of annoyance level is established through least squares regression analysis. Besides, he analyzed the influence of modulated noise, fluctuation, speech intelligibility in the research on the sound quality of train interior noise[41].
- In 2002, KAIST[42] researchers pointed out that different noise components brought different searches when researching vacuum cleaners. Otto[41] indicated that the engine sound quality research model has significant limitations and proposed a roughness calculation model closely related to engine speed information's order
characteristics.
- Honda Company of Japan has conducted in-depth research on the sound quality of vehicles, put forward more than ten factors, such as loud, booming, and sharpness, and finally divided these factors into two

significant categories: sports and luxury. He indicated that the two categories could represent subjective feelings in most populations and establish a relationship between them and psychoacoustic parameters.

- At present, the research on sound quality in the world is not perfect. Under the influence of different cultural backgrounds and environmental factors, the standards for evaluating sound quality are different. Even in the same individual, changes in mental and physiological states can affect the evaluation criteria of sound quality. In addition, because there is no unified international standard for the sound quality evaluation system, different research methods and types are diverse according to the researchers' understanding, so the research results are very different.

1.3.3 Subjective Evaluation

Subjective evaluation research of sound quality adopts the form of subjective evaluation data through questionnaire survey or subjective evaluation experiment to obtain appropriate evaluation terms to describe the subjective perceptual characteristics of sound quality. The specific steps are as follows: First, organize a certain number of listeners to classify sound samples into different annoyance levels. The calculated psychoacoustic parameters were then statistically analyzed with the evaluation results of the jury test. Standard subjective evaluation methods of sound quality include the sequencing method, amplitude adjustment method, scoring method, pairwise comparison method, a semantic segmentation method, etc.

The following are the remarkable achievements made in the development process of subjective sound quality evaluation:

- In 1995, Solomon[43] used the semantic differential method for acoustic research, with different experimental processes for different situations. The University of Oldenburg and Bochum[44, 45] involved various procedures in researching interior vehicle noise and sound quality to apply different research requirements.

- In the same year, Blauert and Bodden concluded through much subjective evaluation research: from a psychological point of view, sound quality mainly has two characteristics: pleasantness and identifiability. In 1997, Farina[46] proposed a subjective evaluation in which the binaural recordings were replaced with a binaural signal that synthesized by two single-channel signals. Gabriella[47] further refined this approach in 2002.
- In 1999, Bodden[48] proposed to cite individual test methods for industrial application purposes. This method can be significantly lower evaluation expenses, but it also causes jumbled evaluation results. Otto[49] introduced the subjective sound quality evaluation system of vehicle noises.

2. SOUND QUALITY CONTROL STRATEGY

2.1 Introduction

Noise control refers to active or passive ways to reduce noise emissions, mainly used to improve environmental problems, personal comfort level, and compliance with government laws and regulations. Effective and practical noise control relies on accurately diagnosing what is causing noise, first by finding the noise source. Once the noise source is confirmed, you can focus on using engineering means to reduce the noise.

Based on the actualization means, noise control can be divided into active control and passive control. Traditional noise control methods include sound absorption, sound insulation, vibration isolation or damping, and mufflers.The principle of these methods is to use of the interaction between sound and materials to convert sound energy into other forms of energy to achieve the purpose of noise reduction. Active control is often implemented by a computer, which is used to generate an anti-noise to counteract the primary noise by interface. Active control has unique advantages in improving sound quality because it can control the noise in a specific frequency band, and it is also easier to change some main psychoacoustic parameters.

The theory and practice of sound quality control and noise control are very similar because their premier objective is to reduce the noise level. However, compared with noise control, sound quality control is more selective and particular. Based on the results of sound quality evaluation, sound control is achieved by removing its annoying noise components as much as possible.

2.2 Noise control

2.2.1 Passive Control

Passive control has played a significant role in noise control over the past few decades. Based on different propagation characters of noise and ambient environment, the classic control methods mainly include vibration damping and vibration isolation for structural-borne noise, sound absorption, and sound insulation for air noise. All four methods are achieved by using appropriate control materials.

With the impact of the development of science and technology, new noise control materials with improved properties are constantly emerging.

In principle, the mechanical energy of elastic waves is converted into the internal energy of the medium to consume and weaken sound waves. The thermodynamic principle dominates the sound absorption principle in medium and high-frequency bands. Therefore, acoustic materials can be regarded as excellent adiabatic materials. That is to say, noise control materials have been a composite material since their development.

Noise control materials mainly have three categories of damping materials, sound-absorbing materials, noise insulation materials: damping materials through increasing the system damping, to reduce noise by inhibiting structural vibration, this measure is called damping vibration reduction; for sound absorption materials, we know that acoustic waves propagation in the medium, will produce acoustic energy attenuation phenomenon. Similarly, when the material absorbs acoustic waves incident into the material surface, part of acoustic energy, thus causing the reduction of acoustic energy, which is called material acoustic absorption; acoustic insulation is a noise reduction method in the noise transmission path, its effect than noise reduction, so acoustic insulation is an effective measure to obtain quiet sound environment. Depending on the mode of acoustic wave propagation, sound insulation is usually divided into two categories: air sound insulation and impact sound insulation, also known as solid sound insulation.

At the same time, acoustics, as a multidisciplinary and interdisciplinary discipline, has also attracted many research forces in different technical directions. The researchers have developed unique phononic crystal and acoustic metamaterials technologies from the cutting-edge perspectives of condensed matter physics and quantum materials in the
multidisciplinary field.

The general characteristics of passive control can be concluded as:

-More effective for high frequency noise

-Easy to apply

-High stability

2.2.2 Active Control

Active noise control is a new technology in the field of noise control in recent years. It participates in the control process by adding additional energy to the noise control process, that is, to artificially produce secondary noise sources or secondary vibration sources to reduce noise, and uses the interference principle of sound waves to control the original noise. This approach is different from the traditional methods, belongs to the active method, or is known as the active method.

Lord Rayleigh[50] first proposed the concept of silencing by the interference of secondary and primary acoustic waves. Later, German Pual Lueg[51] proposed eliminating noise through active control, and in 1935 applied for a patent in the United States entitled "Process of eliminating acoustic oscillations." In 1936, he published an article entitled "Processing of Silence Oscillations," according to the principle of Yang's interference, to achieve the purpose of reducing noise by using the phase elimination interference of sound waves.

In 1953, Olson[52] invented a Feedback active control system which has a different structure from lueg's system. In the 1970s, based on the theory of Huygens, French researchers Jessel[53] and Mangiante[54] proposed a JMC active control algorithm, which can be applied to 3-D free sound fields. In the 1980s, active control was developed rapidly with the wide application of integrated circuits and the rapid development of digital processing technology. With the invention of a high-speed signal processor, self-applicable filters were added to the control system, enabling the system to handle real-time varying environmental noise, a technique known as an adaptive active control.

Since the adaptive filter can automatically adjust its transfer function according to a particular previously set criterion to achieve the desired output, designing the adaptive filter can not have to know the statistical characteristics of its input in advance, and it can also automatically adapt when the statistical characteristics input in the filtering process slowly change over time. These outstanding advantages make it logically accepted and developed by the Active Noise Control Institute. Adaptive active control technology can solve the complex engineering analysis of parameter regulation difficulties caused by noise and environmental characteristics over time and pure acoustic methods.

Based on the input signal to the controller， ANC are classified into Feedforward control and Feedback control[55]：

（1）Feedforward ANC system

The feedforward ANC system directly obtains the reference signal by placing a reference microphone or non-acoustic sensor at the target noise source. The residual noise signal measured by the error sensor and the reference signal obtained by the sensor act as input to the controller, generate and adjust the secondary sound source signal yn, drives the secondary speaker to make secondary noise, interferes with the noise generated by the primary sound source, and finally minimize the sound pressure value at the error sensor.

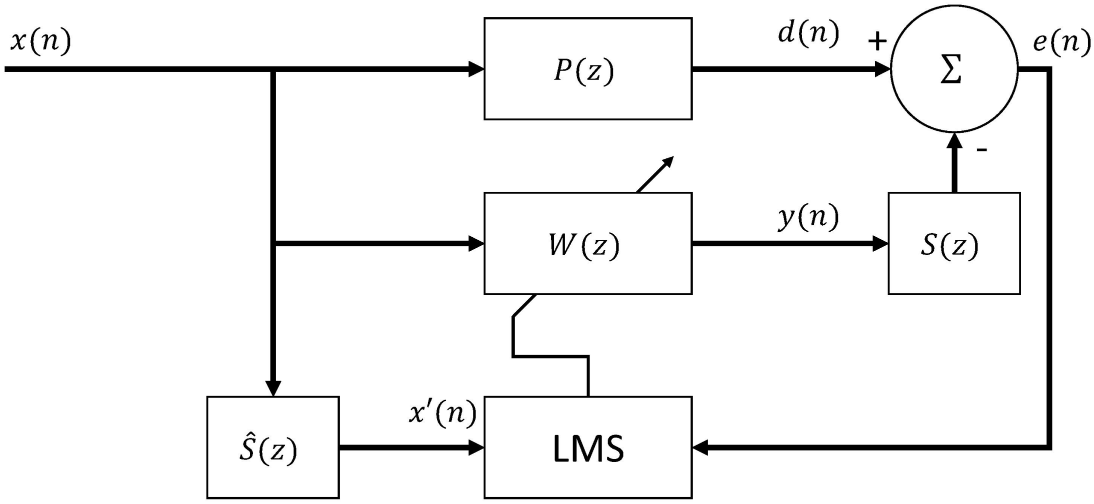


Fig. 2 Feedforward ANC system

（2）Feedback ANC system

There is no sensor in the Feedback ANC system to measure the reference input signal, and only the residual noise after phase elimination interference is obtained through the error sensor and sends it to the Feedback controller, thus achieving the purpose of adjusting the secondary sound source yn, so that it emits the secondary noise opposite to the amplitude of the primary noise amplitude.

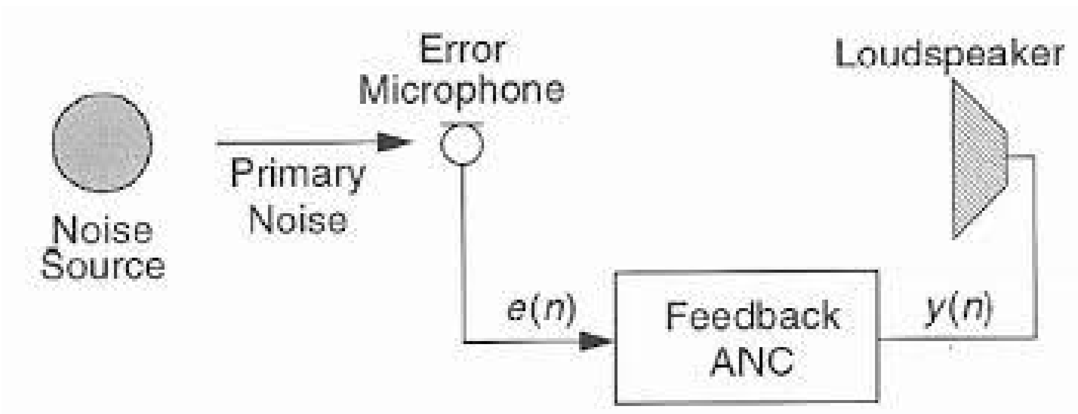


Fig. 3 Feedback ANC system

The Feedback ANC system is simple in structure, with no single

Feedback problem, which can effectively inhibit the transient signal of the system due to particular active damping. At the same time, prone to controller divergence, the system stability is poor; the Feedforward ANC system is robust, not only for narrow-band noise signals but also for broadband noise signals. However, some specific scenarios may not be suitable for installing reference speakers. At present, both structures have been applied in real life. However, the priority of most application scenarios will adopt superior Feedforward ANC systems, and Feedback ANC systems are considered only in some scenarios where reference signals are not easily accessible, accurately obtained, and reference signal sensors cannot be installed.

Depending on the number of channels, the ANC system can also be divided into a single-channel ANC system and a multi-channel ANC system: the single-channel ANC system usually contains only one error microphone and a secondary sound source, which can adopt a Feedforward structure or Feedback structure. The single-channel system has only one secondary pathway, a simple algorithm, simple implementation, but the noise reduction space is limited; multi-channel ANC system generally includes two or more secondary sound sources or error transmitters, secondary pathway number is the product of secondary sound sources and the number of error transmitters of the system, using Feedforward or Feedback structure, the number of reference speakers can be one or more. Multi-channel systems have better noise reduction and more excellent noise reduction space but have poor stability due to too complex systems and algorithms.

2.3 Adaptive Algorithms

Over the past 40 years, many researchers have studied adaptive filters and developed many adaptive algorithms. These include least mean squares(LMS), recursive least squares(RLS), and affine projection(AP), of which LMS is the most widely used.

2.3.1 LMS Algorithms

2.3.2 FXLMS Algorithms

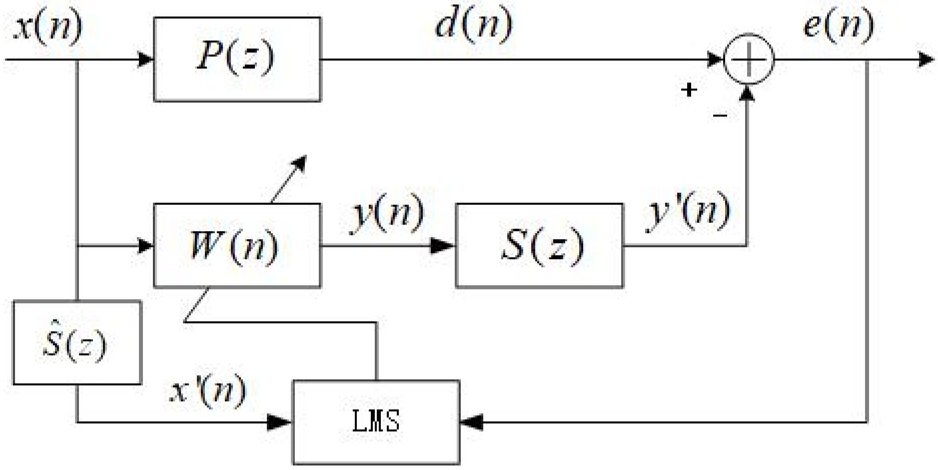


Fig. 4 Blockdiagrams of active control systems using FXLMS algorithm

The LMS algorithm ignores the secondary channel $S(z)$. Due to the existence of the secondary channels, the LMS algorithm usually leads to instability, the error signal is not correctly aligned with the reference signal in time, and there is a delay. Multiple possible protocols can be used to compensate for the influence of the secondary channels. Morgan proposed to place the same filter in the reference signal path to implement the weight updates of the LMS algorithm and hence the so-called FXLMS algorithm. Since $S(n)$ does not necessarily have an inverse, the FXLMS algorithm is usually the most effective method. The FXLMS algorithm was then independently derived by Widrow in the case of adaptive control and Burgess for ANC applications.

Error signal are expressed as

$$e(n) = d(n) - s(n) * \left| w^T(n)x(n) \right| \tag{1}$$

Where n is the time index, $s(n)$ is the pulse response of the secondary path $S(z)$, representing the linear convolution, and $w(n)$ and $x(n)$ are the coefficients of $w(z)$ and the noise signals, respectively. Assuming the mean-square cost function $\zeta(n) = E\left|e^2(n)\right|$, the adaptive filter minimized the instantaneous square error.

$$\zeta(n) = e^2(n) \tag{2}$$

A gradient descent algorithm was used to update the filter weight vector in the negative gradient direction according to the step length.

$$w(n+1) = w(n) - \frac{\mu}{2}\nabla\zeta(n) \tag{3}$$

2.4 Sound Quality Control Strategy Determination

As mentioned in Chapter 1, drone noise consists of some multiple characteristic noise signals. Given the drone operation's open space and operational difficulty, it is challenging to solve all features simultaneously. The range of applications of ANC mainly focuses on the low frequency, corresponding precisely to the frequency band of the drone propeller noise. The depth of the sound frequency band of the speaker is proportional to its size, and eliminating all propeller noise will affect the flight performance of the drone. Considering the above drone characteristics, the schematic feedback LMS algorithm for drone noise ASQC is shown in Figure 5. To avoid the hardware being too complex, the drone carries small speakers and uses smartphones connected via remote control as an error microphone. Since the additional configuration of sensors at the propeller affects the aerodynamic performance of the blade, it is feasible to select single-frequency noise ahead of the drone noise characteristics as secondary noise. The regression equation for sound quality is established via linear regression and is then included in the algorithm to form the complete ASQC system.

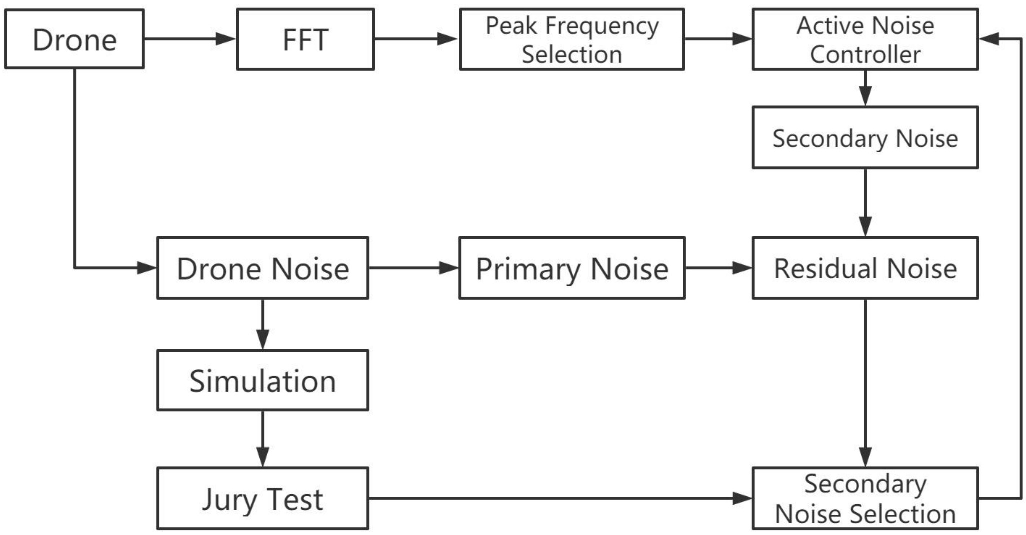


Fig. 5 Blockdiagrams of active sound quality control system

3.DRONE NOISE

3.1 Introduction

In noise research, drones belong to an emerging noise source whose noise characteristics are very different from the traditional noise sources. By the 21st century, with the development of electronic components and communication technology, the cost of drones dropped significantly, and the use gradually expanded to the civilian field. These drones can be classified by weight or flight altitude. For sound quality research, different research methods need to be used for different noise sources and scenarios. Therefore, we need further research to analyze the noise characteristics of the drone.

Table 1 Classification method based on the weight

Type	Weight
Nano	250 g <
Micro Air Vehicles (MAV)	250 g-2 kg
Miniature UAV or Small (SUAV)	2-25 kg
Medium	25-150 kg
Large	> 150 kg

Table 2 Classification method based on the altitude

Type	Altitude	Range
Hand-held	600 m	2 km
Close	1500 m	10 km
NATO	3000 m	50 km
Tactical	5500 m	160 km
MALE (medium altitude, long endurance)	9000 m	200 km
HALE (high altitude, long endurance)	> 9100 m	indefinite

After plenty of experiments, the researchers found that physical closeness of drone receivers and spectral characteristics are different from conventional aircraft. Therefore, many of the conventional aircraft noise research results can not be applied to drone noise studies. On the other hand, improving the drone's nose is also an important topic to investigate its cause profoundly.

In order to improve the sound quality evaluation of the drone and develop the active sound quality control (ASQC) system for the drone's noise characteristics, the actual drone data needs to be collected and analyzed. To this end, an experimental platform was built in the anechoic chamber to collect data of drone noise in different motion states.

3.2 Review of Drone Noise

In the steps of noise research, it is the most important step to explore the way the noise produces. Taking the corresponding solution for the cause of the noise is the most effective method of improvement. In the last few decades, researchers have studied a lot of drone noise production[56].

As researchers have made many achievements in battery research, batteries are being miniaturized and widely used.As researchers study drone technology, today's drones are very different from the original models.In the early days,the noise from a small-scale drone is principally composed of propeller noise and engine noise[57, 58].

After most civil drones used electric propulsion to replace fuel engines, propellers became the primary source of the noise[59]. Propeller noise consists of two parts: rotation noise and broadband noise[60]. There are three main sources of broadband noise: （1）leading edge noise, which is generated by volume displacement and aerodynamic loading on the surface of the blade； （2）trailing edge noise， which is due to the interaction between the blade trailing edge and the turbulent boundary layer; and（3）separation noise, which is generated by the separation of flow on the blade airfoil[61, 62].

3.3 Experiment and Analysis

3.3.1 Description of the Drone Noise Acquisition Experiment

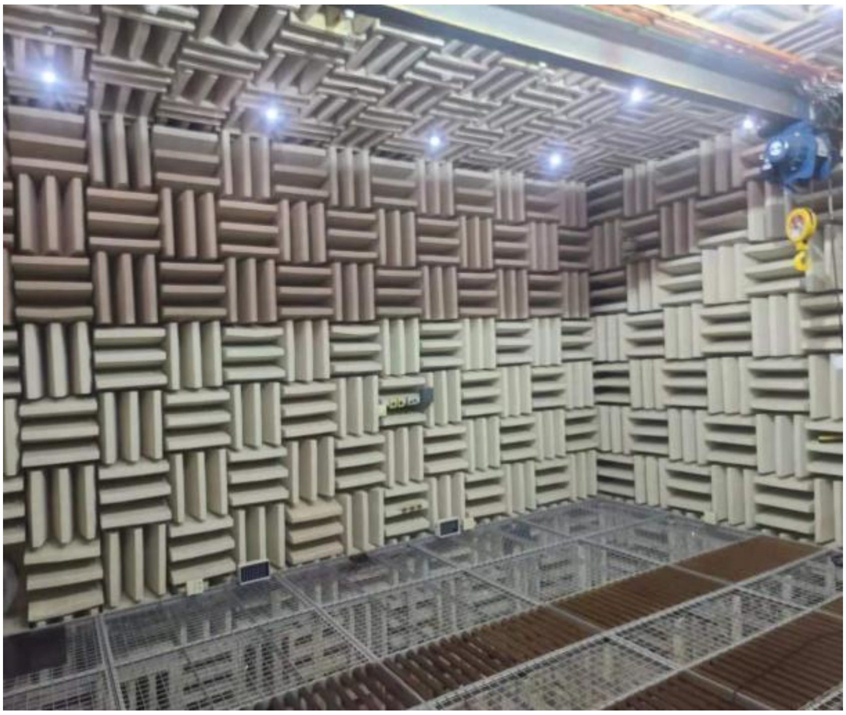
The proposed experiment was developed in two phases. Firstly, noise acquisition was performed for the drones in different motor states using microphones. Secondly, the most relevant data obtained were selected for the ASQC simulation.

The noise from the drones was measured inside an anechoic chamber at the University of Ulsan. The detailed parameters of the anechoic chamber are presented in Table 3. To ensure accuracy of the collected data, professional acoustic equipment was used for the measurements. Figure 1 shows the acoustic equipment and drones used in the experiment. An ABSWA MPA201 free-field microphone was connected to a SCIEN ADC 3241 professional sound card through a BNC connector cable. The drone had dimensions of 83mm (H) × 83 mm (W) × 198 mm (L) with two pairs of MAVIC 8330 quick-release folding propellers measuring 5 mm (H) × 40 mm (W) × 50 mm (L). Remote controls were used to control the drones viewed as a source of noise, and laptops were used to control any other devices.

Table 3 information about the test room

Room type	**Room size**			**Volume (m3)**	**Temperature (°C)**	**T60 (s)**
	Length	**Width**	**Height**			
Anechoic chamber	8.4	7.2	6.0	363	227	< 0.08

(a)



(b)

Fig. 6 The experiment site and drones: (a) Anechoic chamber; (b)DJI Mavic Pro drone.

The signal data acquisition and computing were performed using the MATLAB software. In the experiments, signal acquisition was performed using two microphones to reduce error. The microphones were set 1.5m from the drone, and the angle between the two microphones and the drone connection was 90°. The microphones were each installed on a tripod with a relative distance of 1.5 m from the floor. The drone then performed take-off and landing operations from a board placed on the ground. The overall equipment layout is shown in Figure 7.

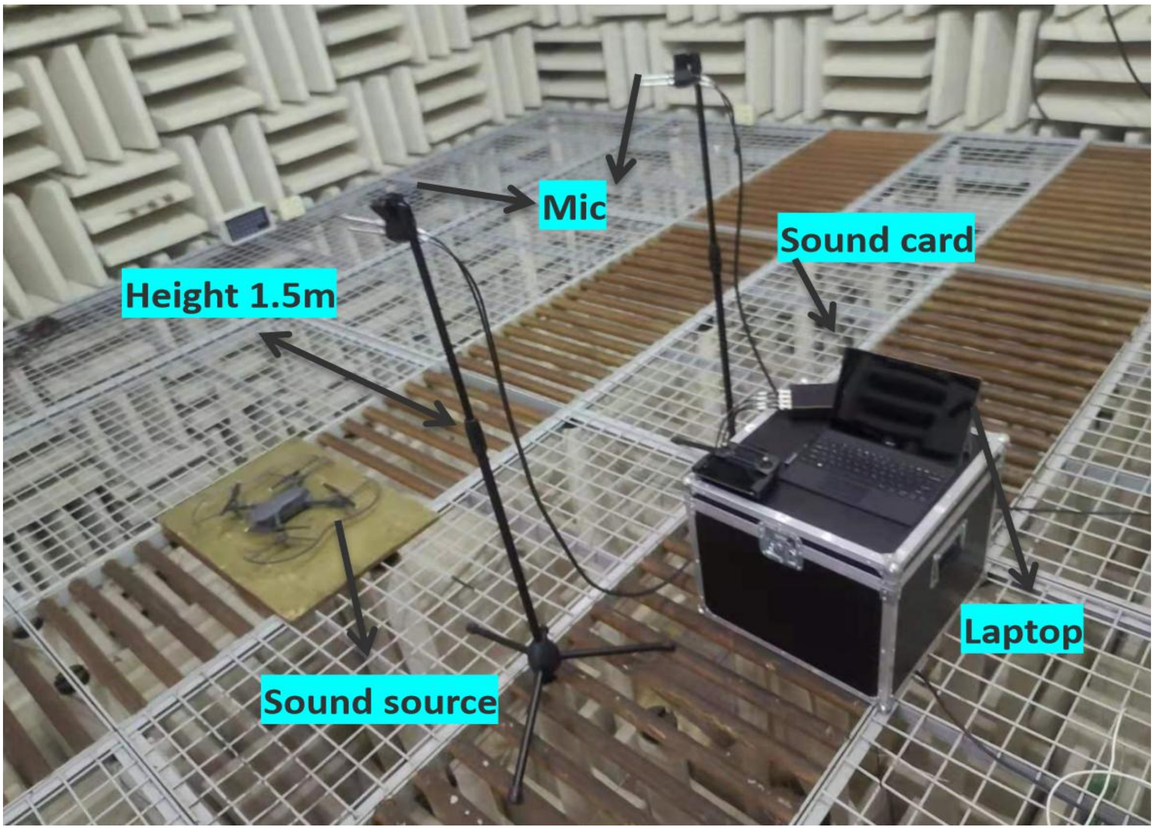


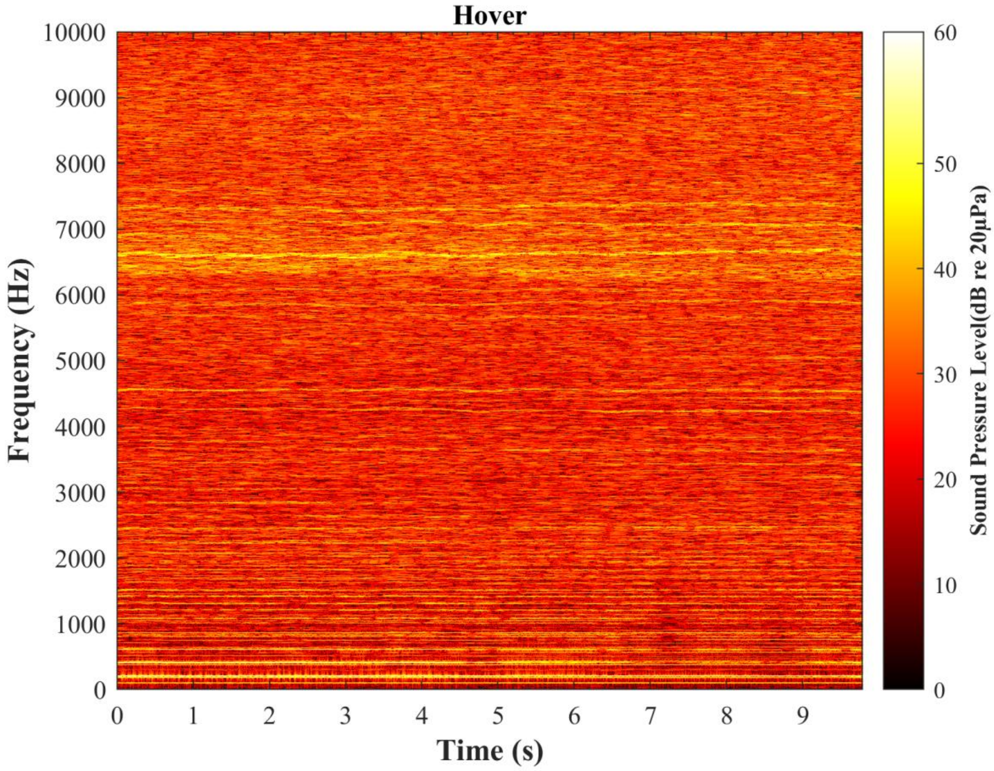
Fig. 7 Equipment layout of drone signal data acquisition in the anechoic chamber

According to the above-mentioned experimental configuration, the noise signals of a DJI Mavic Pro drone with a length of 10 s and a sampling rate of 48,000 Hz were measured using the proposed data acquisition system（hover，take off and horizontal flight）. The collected noise signals are saved in a laptop in the .wav format, which will be used for evaluation and simulation of the ASQC method.

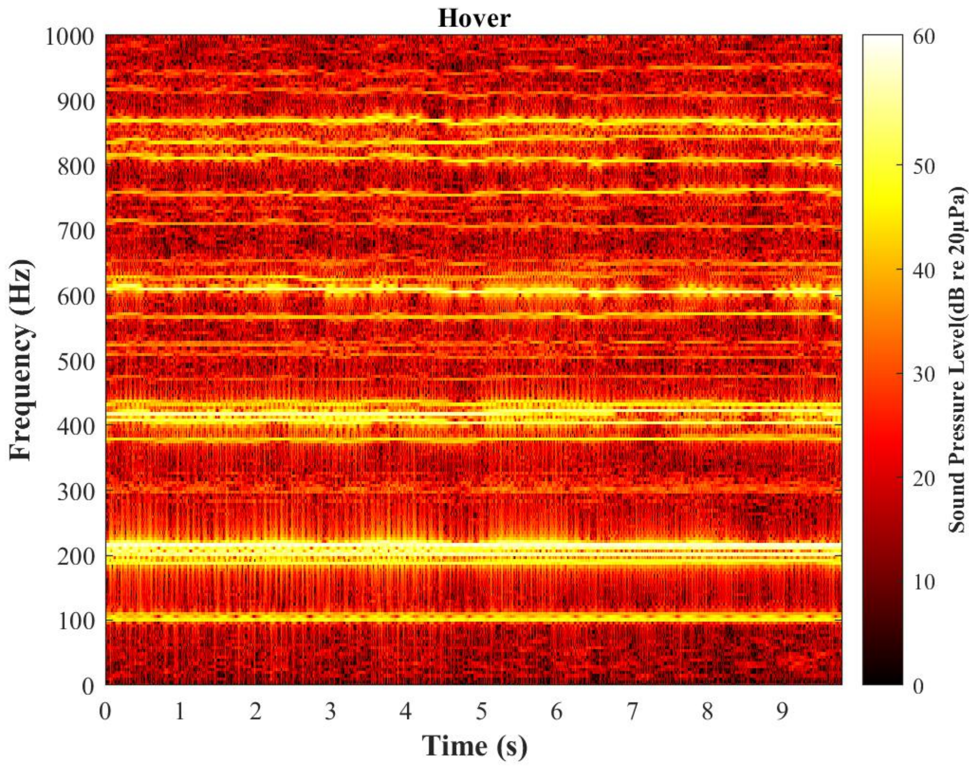
3.3.2 Result Analysis

A spectrogram is a visual representation that can express the frequency and intensity of the sound signal as it varies with time[63]. It uses a distribution of different colors from the image to visually show changes in the drone noise signal. The spectrogram of drone noise can be observed in figure. As seen in Figure 4, the drone radiates significant high frequency noise in the 6 kHz to 8 kHz frequency bands. After consulting the literature and experimental verification[14, 64], this part of the noise can be explained by the self-noise of the propeller blades, motor noise, and cooling fan noise. The sound produced by drones is mainly tonal in character， which usually has tonal components in a low-frequency range corresponding to the blade pass frequency (BPF) and their harmonics. Since the rotors of drones often have different rotating speeds and phases, the tonal components are not located in a single frequency, but instead distributed around their center frequency. In Figure 8, the spectral line corresponding to the rotor BPF is around 200 Hz. In this experiment, to obtain the sharpest contrast result, the noise data of the drone in the hovering state will be used as the sample.

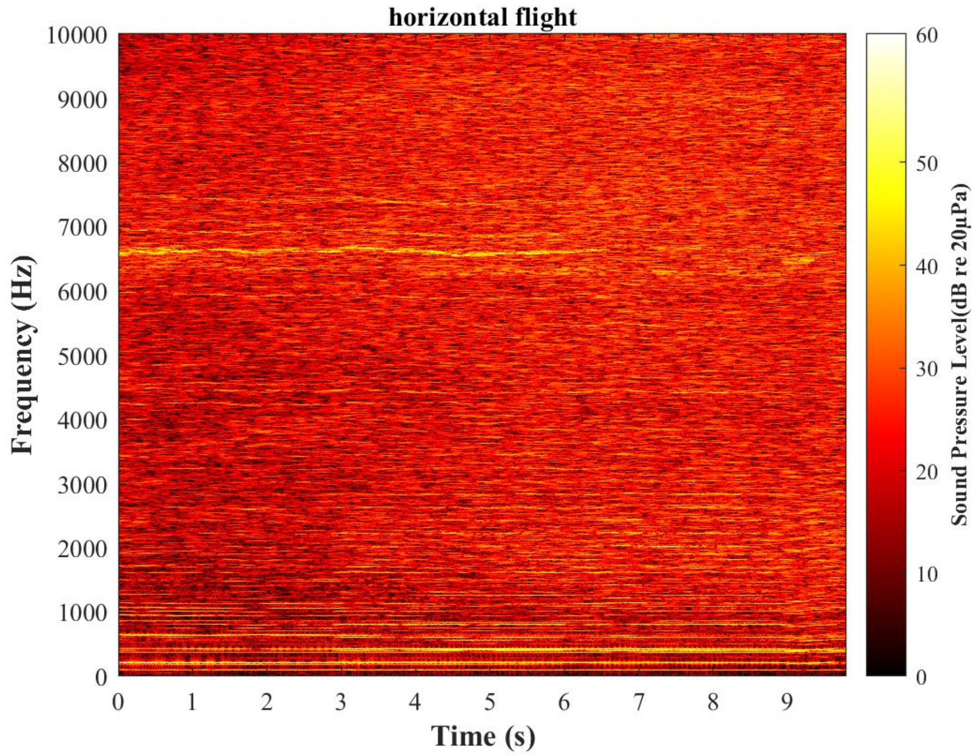
(a)


Hover
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Frequency (Hz)
0
1
2
3
4
5
6
7
8
9
Time (s)
60
50
40
30
20
10
0
Sound Pressure Level(dB re 20μPa)

(b)


Hover
1000
900
800
700
600
500
400
300
200
100
0
Frequency (Hz)
0
1
2
3
4
5
6
7
8
9
Time (s)
60
50
40
30
20
10
0
Sound Pressure Level(dB re 20μPa)

(c)



(d)

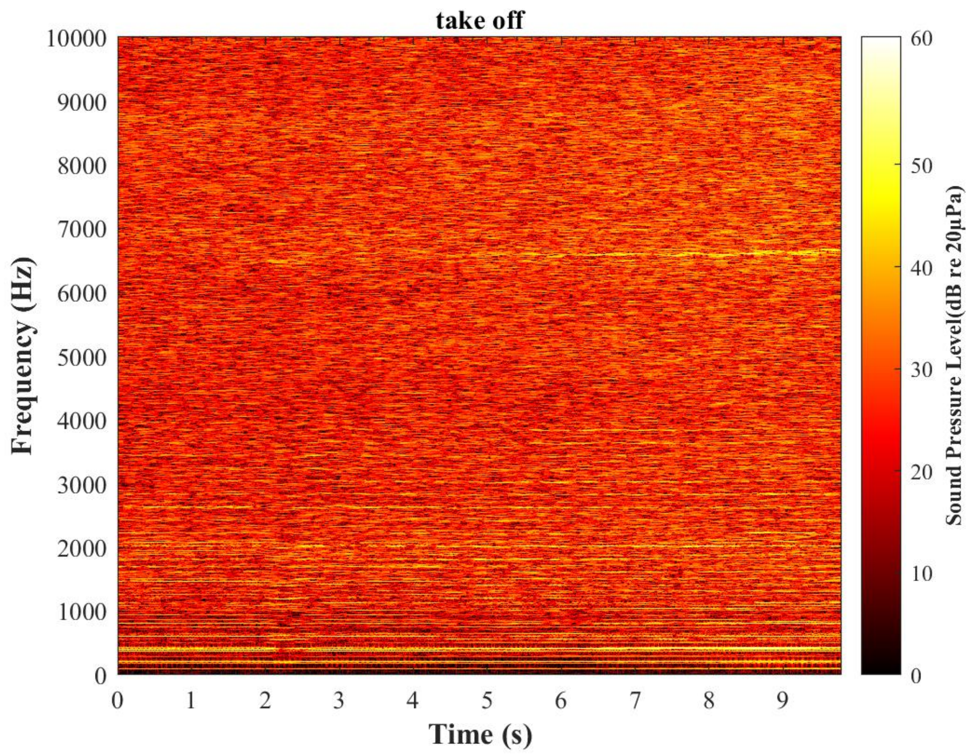


Fig. 8 Spectrogram of the drone in the anechoic chamber: (a) Hover, 0-10000 Hz; (b) Hover, 0-1000 Hz; (c) Horizontal 126 flight; (d) Take off.

4 Sound Quality Evaluation

4.1 Introduction

In this chapter, computational models of several standard psychoacoustic parameters are first introduced, and subsequent simulation experiments of active sound quality control (ASQC) systems using Matlab software to obtain simulation results. The obtained audio data were subjective and objectively evaluated, and the regression analysis was used to obtain the computation of drone sound quality.

4.2 Objective Sound Quality Evaluation

4.2.1 Objective modeling of Sound Quality Metrics

（1） Loudness

Loudness quantitatively reflects the subjective feeling of the human ear on the strength of the voice. Loudness is a kind of evaluation quantity between subjective and objective, which is the decisive characteristic quantity in sound quality evaluation. Generally speaking, the larger the loudness value, the more serious the degree of annoyance caused by people, and the lower sound quality, but the loudness is not the decision standard of the noise and sound quality.

The numerical value of loudness is equal to the SPL of 1 kHz pure tone with the same loudness. The relation between loudness and loudness level is given:

$$N = 2^{(L_N - 40)/10} \quad \text{or} \quad L_N = 33.3\log_{10} N \tag{4}$$

The loudness considers the physical characteristics of the sound and the spectral distribution and the effect of the human ear asking effect on the sound, which can reflect the loud level of the human ear more accurately than the A-weight SPL. The loudness is in sone and defines 1 kHz, 40 dB reference pure tones as 1 sone. If a sound sounds twice as much as the reference sound, the loudness is recorded as 2 sone. The loudness cannot be directly obtained by sound intensity listening threshold curves but can only be constructed by methods such as amplitude estimation.

For steady-state noise loudness calculations, the International standard ISO-532 specifies two calculation methods of A and B.Method A adopts the computational model proposed by Stevens, using octave frequency band or 1 / 3-octave frequency band spectrum, suitable for the loudness calculation of diffusion sound field of the flat spectrum; Method B uses Zwicker, using 1 / 3-octave frequency band as the basic data to modify the masking effect of the human ear, which is suitable for the calculation of free or diffusion sound field.

In addition to the incident direction, the loudness curve is also determined by three factors: bandwidth, spectrum, and duration.

$$N = \int_{0}^{24Bark} N'(z)dz \tag{5}$$

（2）Sharpness

Sharpness is a measure of the high frequency energy content of a sound, and the unit of sharpness is acum. It’s the matric which is defined by Zwicker and Fastl[65] as“a narrow band noise on critical band wide at centre frequency of 1 kHz having a SPL of 60dB”. However,the metric of sharpness has not yet been standardized.

There are several methods to calculate the metric, including:

Von Bismarck’s method[66] introduces the idea of a weighted first-moment calculation, Aures’s method[67], which is a modified version of Von Bismarck’s equation, and Zwicker & Fastl’s method which is a version of Von Bismarck’s equation with a modified weighting curve.

$$S = 0.11\frac{\int_0^{24Bark} N'g'(z)zdz}{\int_0^{24Bark} N'dz} \tag{6}$$

The weighting function $g(z)$,which depends on the critical band rates, is determined by

$$\begin{cases} z<14, \rightarrow g(z)=1 \\ z\geq 14, \rightarrow g(z)=0.00012\cdot z^4-0.0056z^3+0.1z^2-0.81z+3.51 \end{cases} \tag{7}$$

Like the definition of specific loudness, the specific sharpness of each critical band may be expressed as

$$S' = 0.11\frac{N'g'(z)z}{\int_0^{24Bark} N'dz} \tag{8}$$

(3) Roughness

Roughness is a psychoacoustic parameter describing the degree of modulation of a sound signal, which reflects the magnitude of the signal modulation amplitude and the modulation frequency distribution, which is suitable for evaluating sounds from 20 to 200 H z modulation frequency 30, particularly for sounds around 70 Hz. The time-domain structure of the sound signal, the frequency distribution of the modulation, the modulation frequency size, the modulation degree, and the different degree of the sound pressure level determine the size of the roughness.

There is currently no international standard for the calculation of roughness, with the commonly used formula of:

$$R = 0.011\frac{\int_0^{24Bark} \Delta L_E dz}{(f_{\text{mod}} / f_0) + (f_0 / f_{\text{mod}})} \tag{9}$$

In the formula: ΔL_E is the amplitude of sound pressure change in the critical frequency band; f_{mod} is the modulation frequency; f_0 is the modulation base frequency, and f_0 =70 Hz.

Human hearing system has a peculiarity that can be described as: if the duration of a sound is greater than 300 ms, the subjectively perceived length of the sound is equal to its actual length; if the duration of the sound is shorter than 300 ms, the subjectively perceived length of the sound may be different with its actual length. For example, a sound with a length of 10 ms may be subjectively perceived to be 20 ms long. This peculiarity of the auditory system has important consequences for the subjective perception on instantaneous sounds, such as rough sounds.

Thus the metric of roughness has not been standardized and there are several proposed calculation methods. For example, Aures[68] proposed a method in 1985, wherein the product of ΔL_E and f_{mod} in each critical band is estimated with a generalized modulation depths mi^* and a weighting function $g(zi)$. Widmann and Fastl[69] proposed another method for calculation, wherein the specific loudness is measured every 2 ms to calculate a time variable course of the masking pattern and from this a value of ΔL_E can be evaluated. In this work, the roughness is calculated via a developed model which is based on the Daniel and Weber's model[70]. With this model, the temporal masking depth and the modulation frequency can be accurately estimated. Figure 9 is a standard flow chart of the roughness calculation model.

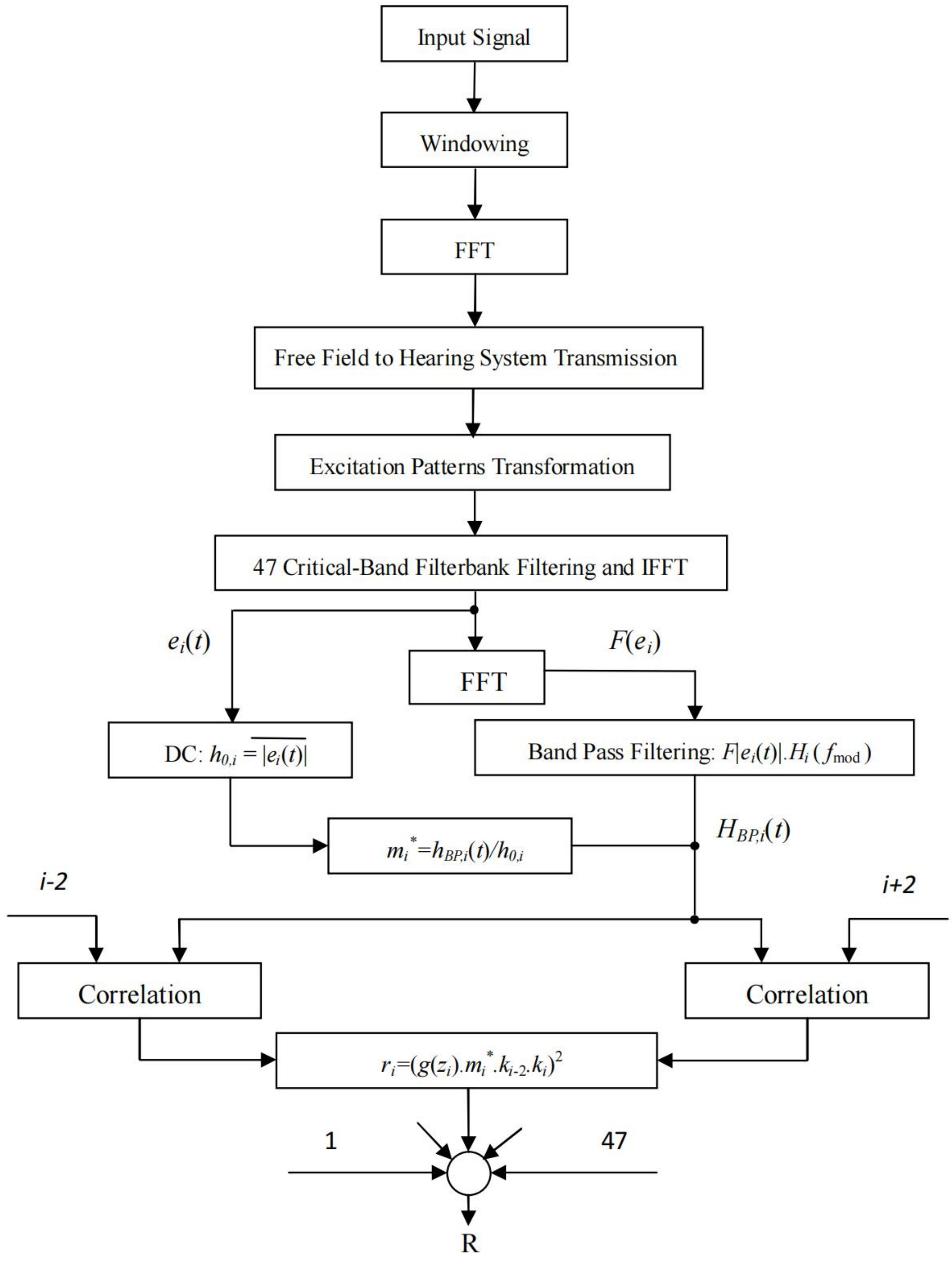


Fig. 9 Structure of the roughness model

（4）Fluctuation Strength

The fluctuation strength describes the degree to which the human ear feels about the slow-moving modulated sound, adapted to evaluate the low-frequency modulated sound signals below 20 Hz, reflecting the loud ups and downs of the sound subjectively felt by the human ear. Car noise usually causes fluctuating auditory feeling, so fluctuation strength is a more sensitive identification parameter.

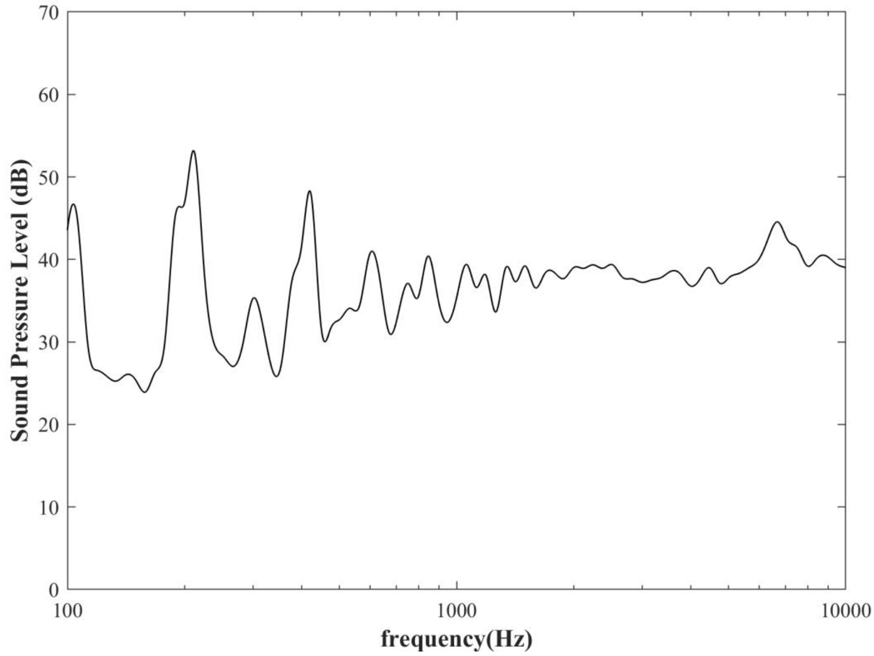
There is no unified international standard for the calculation of fluctuation strength, and the typical Zwicker formula is calculated as follows:

$$F = 0.36 \frac{\int_{0}^{24Bark} \lg(N'_{\max} / N'_{\min}) dz}{(f_{\text{mod}} / f_0) + (f_0 / f_{\text{mod}})} \tag{10}$$

4.2.2 Experiment and Analysis

First, perform time-domain SPL and loudness analysis on the selected drone noise data.. The loudness is calculated following the Zwicker model[31] in the standard ISO 532-1, and the computation is expressed as Eq. 5. Here, N is the overall loudness and $N'(z)$ is the characteristic loudness under the bark domain. The results are shown in Figures 4 (a) and (b), and it is clear that the linear SPL and loudness are not synchronous changes. Loudness is one of the psychoacoustic parameters and the most important index of sound quality evaluation, and they provide a way to measure the subjective sensation that sounds can produce regarding human listeners. As research in the field of sound quality becomes increasingly active, the improvement goals of sound design and noise improvement techniques have helped improve the subjective responses that sound causes. Therefore, in the study analysis, we should also analyze other psychoacoustic metrics for drone noise.

(a)



(b)

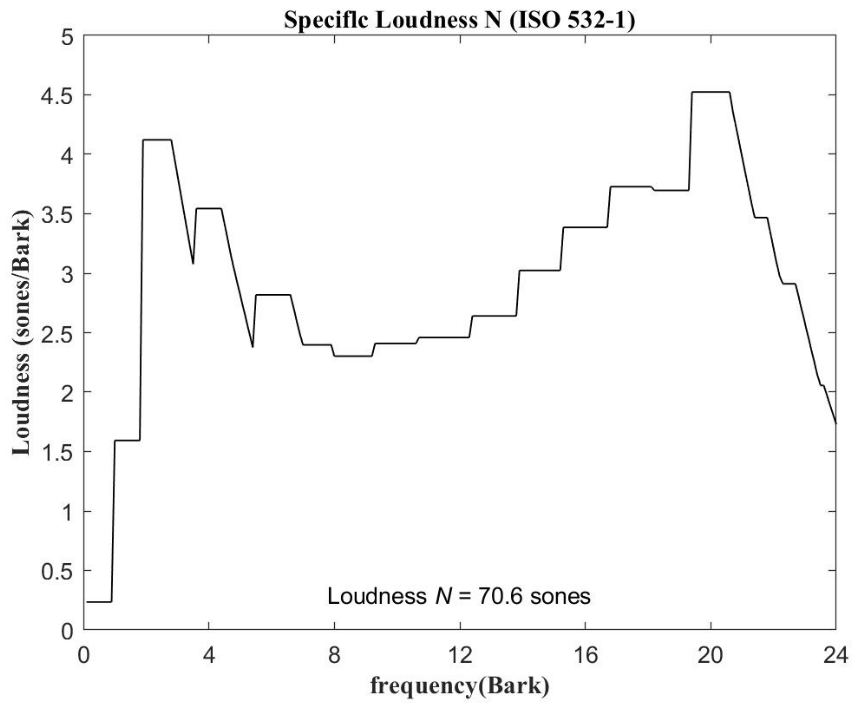


Fig. 10 Noise characteristics of drone: (a)Bands spectra of the drone; (b)Loudness index curves for drone.

By analyzing the frequency map of the drone noise (shown in Figure 10), the single frequency signals of 216.9 Hz, 418.8 Hz, 605.8 Hz, and 866.8Hz were chosen, where the SPL peak were selected as secondary noise. The filter length and size of the step length factor largely determine the convergence and stability energy of the ANC system. To determine the convergence effect and convergence rate, the length of the filter was fixed to 120 after multiple experiments. For the step length factor, it is typically seen that a larger μ results in faster algorithm convergence; however, the larger the steady state error, the smaller the μ and the slower the algorithm convergence. That said, this resulted in a smaller steady state error. To ensure steady-state convergence of the algorithm, μ should lie in the following range:

$$0 < \mu < \frac{2}{\sum_{i=1}^{N} x(i)^2} \tag{11}$$

Within the range of values, we selected 6 sets of values combined with 4 secondary noise, and conducted simulation experiments through the written Matlab program to obtain 24 sets of audio data.

We performed a loudness analysis of 25 sets of audio, including the original data, and the resulting mean loudness curve is shown in Figure 11. It is clear that a significant correlation between combinations of control conditions and loudness values.

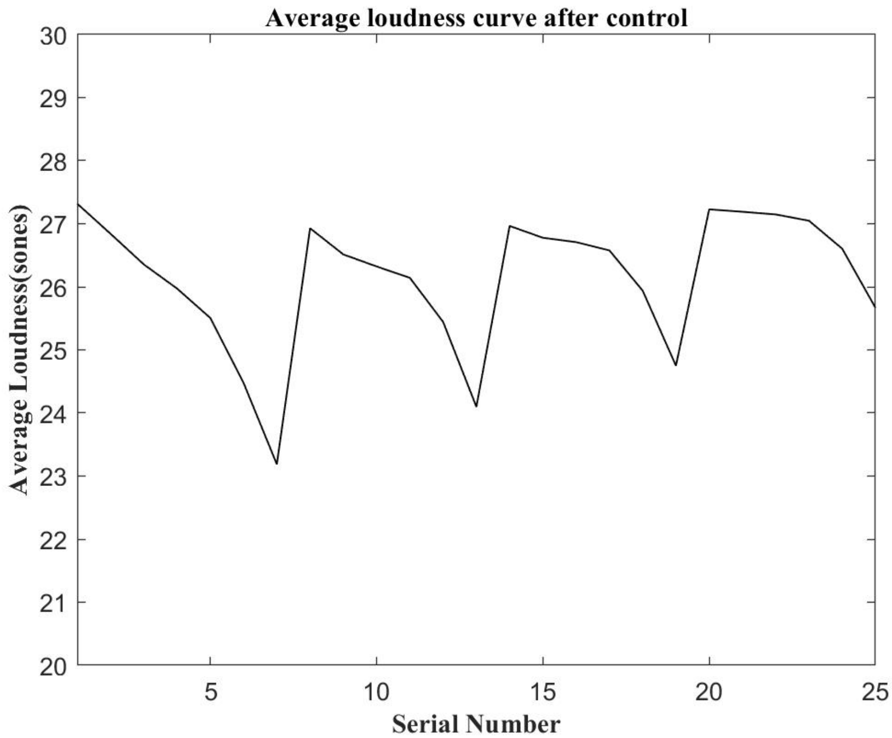
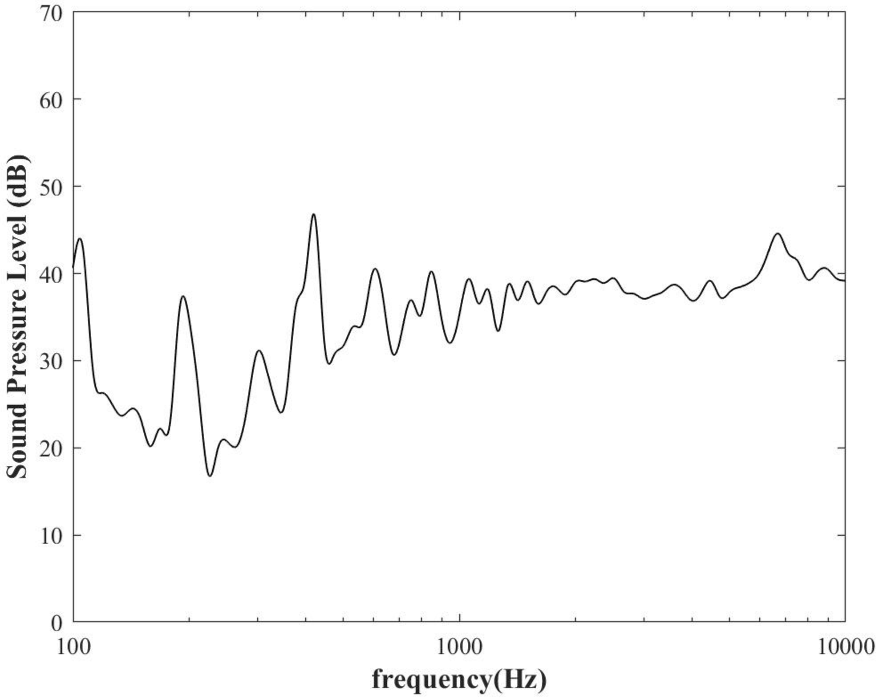


Fig. 11 Average loudness of simulated results and original data.

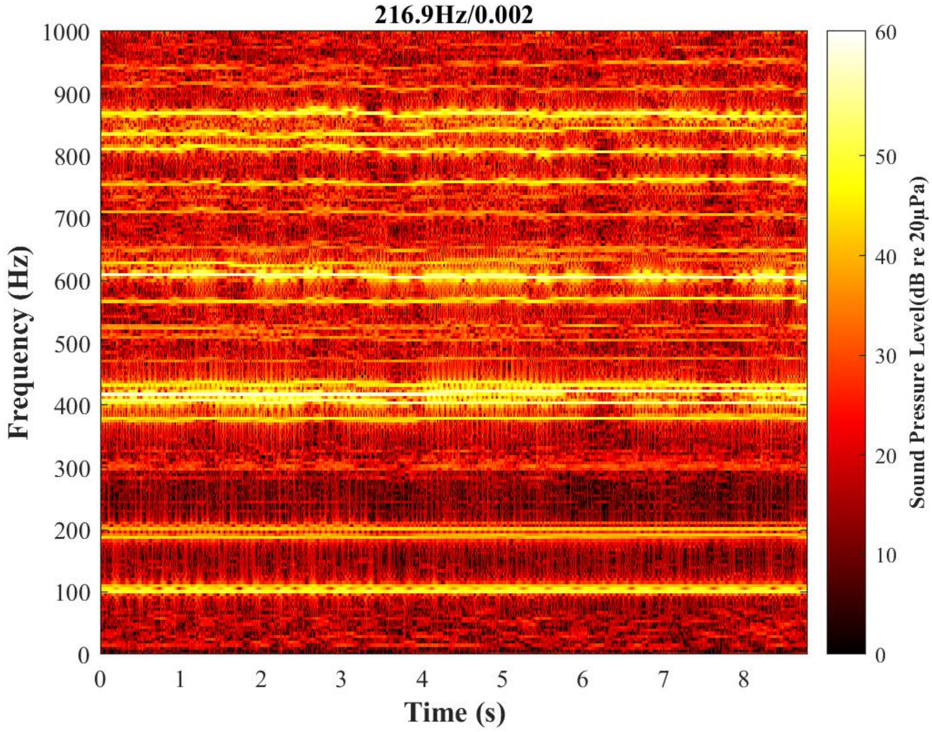
Figure 12 shows the signal data obtained from simulation experiments with a secondary noise of a 216.9 Hz/866.8 Hz and a step length of 0.002. As can be seen from the figure, the SPL of the frequency band corresponding to the secondary noise is significantly reduced. Since the purpose of this experiment was not to reduce the SPL, but to improve the sound quality, we conducted further analysis of the psychoacoustic parameters of the signal.

(a)



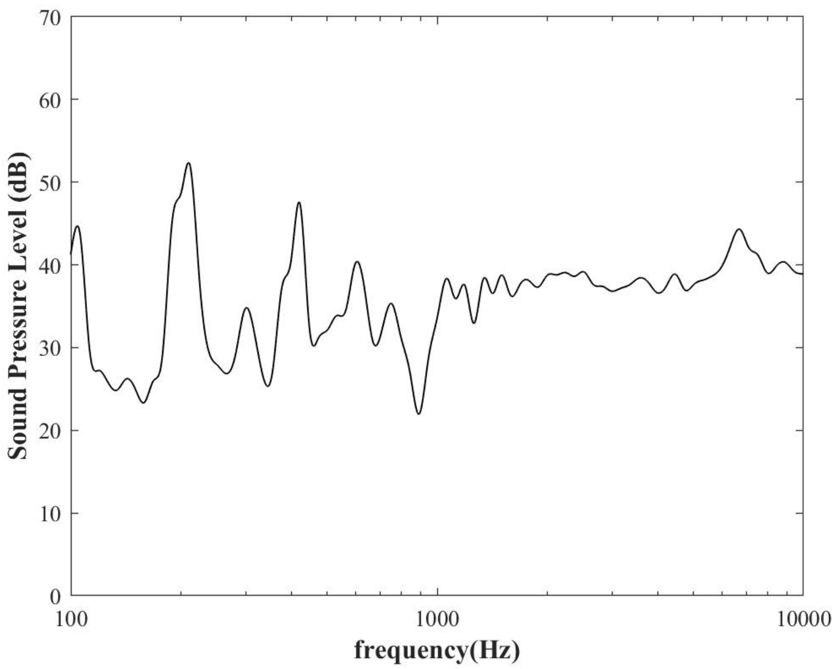
70
60
50
40
30
20
10
0
Sound Pressure Level (dB)
100
1000
10000
frequency(Hz)

(b)



216.9Hz/0.002
1000
900
800
700
600
500
400
300
200
100
0
Frequency (Hz)
0
1
2
3
4
5
6
7
8
Time (s)
60
50
40
30
20
10
0
Sound Pressure Level(dB re 20μPa)

(c)



(d)

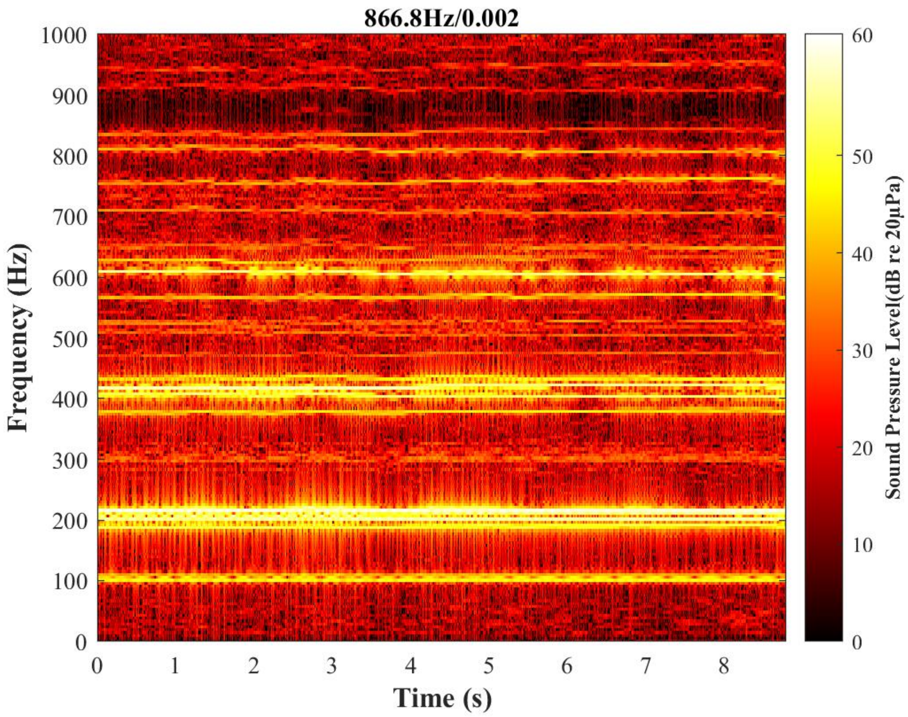


Fig. 12(a) Band spectra of signal after ASCQ (216.9 Hz/0.002 step length); (b) Spectrogram of signal after 183 ASCQ (216.9 Hz/0.002 step length).(c) Band spectra of signal after ASCQ (866.8 Hz/0.002 step length); (d) Spectrogram of signal after 183 ASCQ (866.8 Hz/0.002 step length).

Through research and analysis, loudness is not the only objective parameter that affects sound quality. That is, other parameters are also significantly related with sound quality. In the objective data analysis, if only the loudness analysis is performed, there may be large deviations from the real sound quality, so a more accurate analysis strategy is needed.

To accurately analyze the influence of the ANC system on sound quality, four common psychoacoustic parameters were studied: loudness, roughness, sharpness, and fluctuation strength. The A-weight sound pressure levels were also introduced as a reference. Table 4 shows the results for each psychoacoustic parameter. It is obvious that the changes of the four parameters were not synchronized, so it is difficult to evaluate the integrated acoustic quality performance of the signal through objective values alone.

Table 4 Psychoacoustic parameters of sound quality before and after control

Data type	SPL	loudness	roughness	sharpness	fluctuation strength
Original data	63.618	27.3172	0.086279	2.401	0.175626
216.9hz/0.002	63.0275	25.5059	0.08697	2.5608	0.017687
886.8hz/0.002	63.5887	27.0477	0.080074	2.4264	0.17142

4.3 Subjective Sound Quality Evaluation

4.3.1 The Necessity of Subjective Sound Quality Evaluation

We know that in the evaluation of sound quality, people are the main body of noise feeling. Through the subjective listening jury evaluation of noise, we can deepen the understanding of product sound quality, better reflect the needs of customers, and point out the direction for improving product sound quality. Human auditory perception is the ultimate criterion for evaluating sound quality. These perceptions cannot be measured directly measured with current techniques. Although some objective parameters (SQMs) can gratefully describe these perceptions, they often need to be estimated by subjective assessment (e. g., a jury hearing test). At present, no objective method can completely replace the subjective evaluation of sound quality, and its effectiveness should be tested by subjective evaluation. In this sense, subjective evaluation is the most accurate and is the basis of sound quality research. Therefore, in recent years, people have paid attention to the characteristics of people as the subject of noise sensation in the research of noise and put forward many subjective evaluation methods, mainly including classification method, grade scoring method, pairwise comparison method, semantic analysis method, and rating scale method and other methods.

4.3.2 Subjective Sound Quality Evaluation methods

The subjective evaluation of sound quality uses the method of experimental psychology to classify the quality of the test sound. Subjective evaluation involves many factors, including selecting test objects, noise preparation, listening environment, and the selection of evaluation methods. The evaluation method of the listening jury is the main influencing factor, and the main methods are:

（1）Pairwise Comparison

Renowned psychologist Thurstone[71] first proposed the pairwise comparison method in 1927. This is a comparative evaluation method, and the specific is first to group the sample sound pairwise and then play by a group so that the listening object can make a relative comparison of the relevant parameters of the two sound signals.

For sound evaluation, the listening object needs to compare the constituent playing sound according to the evaluation criteria. The standard of evaluation can be any meaningful parameter, typically such as good and bad sound, annoyance, loudness, roughness, and other metrics.For example, in a group which contains Sample A and B, if A sounds better than B, then A is scored 2 points, and B is scored 0 point; if A sounds similar to B, then both of A and B are scored 1 point. After summing the scores of a sample in all related compassion, the summation is regarded as the evaluation result for the sample.

The pairwise comparison method is relative, not absolute. The listening object does not have to consider before and after the judgment. Pairwise comparison is different from what people make in daily life. It is very natural and convenient for untrained listeners. The disadvantage of the pairwise comparison method is that the number of groups when the number of sounds is too large.

（2）Rating scale

The rating scale method is to divides the noise quality into several grades. In the trial, the evaluation person gives the corresponding evaluation score according to their respective subjective perception degree and takes all scores of a sound with the arithmetic average as the sound quality level of the sound. The key to the method is to determine the appropriate scoring scale.

With this method, the work of each listener is not much compared with other methods. The disadvantage of this method is that an experienced and skilled jury is required for obtaining accurate evaluation results. So before the test, the jury is often needed to be trained with some fundamental rating skills.

（3）Semantic Differential

The pairwise comparison method only focuses on one sound property, and the semantic differential method can evaluate multiple properties of sound. Listening objects use many opposite modifiers (semantic pairs) to describe the heard sound. If the noise properties are described in more detail, they can be divided into several levels in the middle of these modifiers, but not to listen to the object evaluation, the number of levels can not be too much, usually the most common to be divided into 5 or 7 levels. The choice of these semantic pairs should be consistent with the task, and the choice of evaluation parameters should be as far as irrelevant as possible. Semantic differential is usually suitable for providing an initial description of sound properties, combined with subsequent factor analysis to give the representation dimension of sound properties.

4.3.3 Evaluation Scheme Determination

In this work, a subjective evaluation was implemented to determine the relationships with objective measurements and thus would need to evaluate the sound quality in each sample as accurately as possible. Considering the lack of skillful evaluators, simple sorts, numerical estimation, and semantic differential are not suitable methods. Pairwise comparisons alone are also complicated because many sound samples are needed to obtain the most general results. Therefore, this work uses a combination of rating scale and pairwise comparison. Let the jury first listen to a set of test data to have a detailed understanding of the noise of the drone. The 25 sets of audio were then divided into five large equivalents, using the pairwise comparison method in the second round of judgment, scoring samples with similar subjective perception, and eventually dividing into 15 grades.

The jury members of the organization are all engineering students from Ulsan University, mainly male, aged between 20 and 35.Experiments were performed in the anechoic chamber and used AKG K52 professional listening headphones for playback.

Twenty-five audio copies including the original signal were tested, each consisting of noise pairs before and after control.The jury members heard each audio copy and rated the improvement.The degree of improvement was divided into five grades and divided into three different scores under each grade, and the scoring table is shown in Table 5.The evaluation is divided into two rounds: the first round of grade evaluation; the second round repeatedly compares the same grade of audio, and gives the score value.

Table 5 Grade scoring scale

Improvment	**No improvement**			**Basically no improvement**			**A little improvement**			**have improved**			**A significant improvement**		
Socre	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Audio 1															

4.3.4 Result and Analysis

Peoples' subjective feelings and personal preferences have a strong correlation. Therefore, when evaluation results appear, such subjective opinions should be abandoned and instead focus should be on the evaluation results of most people. After data screening of the evaluation results, the jury subjective evaluation results of the 25 sets of signals are shown in Table 6.

Table 6 Subjective evaluation results.

Audio	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Score		2.71	4.71	6.00	7.14	9.85	13	2.28
9	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
3.57	4.86	5.42	7.00	10.57	4.28	4.85	6.28	6.14
18	**19**	**20**	**21**	**22**	**23**	**24**	**25**	
9.14	9.71	1.28	2.57	2.58	3.85	5.42	8.42	

The table shows that the 216.9 Hz signal works better as a secondary sound source with the same step length; with the same secondary step source signal, the step length was larger. Most of the jury members gave positive reviews, and they considered an overall improvement of 30-50 %. It can be seen that the ANC system has an obvious effect on improving the sound quality.

4.4 Linear Regression Analysis

In order to study the interrelationship between the subjective evaluation results of sound quality and the objective parameters of psychoacoustic, we analyzed the subjective evaluation value of the subjective evaluation, and analyzed the A-weighted SPL as a reference. Linear-correlation analysis is a statistical method for analyzing the close degree of linear correlation between variables, generally measured by a specific statistic describing the correlation relationship, namely the correlation coefficients. In this study, the correlation coefficient between the sound quality evaluation grade and each objective parameter is shown in Table 7.

Table 7 Correlation coefficient between the sound quality evaluation grade and objective parameter.

		Score	Loudness	Roughness	Fluction strength	Sharpness	A-Weight SPL
score	**Pearson Correlation**	1	-.928**	-.007	-.103	.921**	-.685**
	Sig.(2-tailed)		.000	.976	.632	.000	.000
	N	24	24	24	24	24	24

As seen in Table 7, two of the four main psychoacoustic parameters have obvious correlations with the sound quality evaluation rating, all above 0.8 (roughness and sharpness). Definitions of correlations in the statistics are shown in Table 8. Note that the noise collection in this paper was conducted in the noise chamber, and the roughness and volatility were not particularly complex. In addition, based on Table 7, the three A-weighted SPL are highly correlated with the sound quality evaluation results, but the correlation coefficient is also less than the two psychoacoustic parameters of roughness and sharpness. This indicates that it is more appropriate to measure drone psychoacoustic parameters rather than A-weighted SPL.

Table 8 Correlation rating system

correlation coefficient	$\lvert r \rvert = 0$	$0 < \lvert r \rvert \leq 0.3$	$0.3 < \lvert r \rvert \leq 0.5$	$0.5 < \lvert r \rvert \leq 0.8$	$0.8 < \lvert r \rvert \leq 1$	$r = 1$
correlation intensity	zero correlation	weak correlation	low correlation	significant correlation	highly correlated	completely correlation

After clarifying the above correlations, multiple linear-regression analysis was performed to determine the relationships that were objectively quantified describing the subjective evaluation results of acoustic quality using psychoacoustic parameters.Regression analysis is a statistical analysis method to determine the quantitative expression between a dependent variable and several independent variables, namely acoustic quality subjective evaluation scores, and independent variables are various psychoacoustic parameters. A mathematical model of formula (12) was first obtained by excluding roughness and fluctuation strength by F test following stepwise regression (stepwise). The composite correlation has a coefficient of 0.857 showing good fitting property.

$$SQ = A \bullet Ld + b \bullet Sp + c \tag{12}$$

It can be seen that the four main psychoacoustic parameters are significantly correlated with the subjective evaluation results of drone noise. The correlations between loudness, roughness, and sharpness are large, where the correlation with loudness is the largest. Therefore, to improve the sound quality of drones, attention should be paid to the loudness, roughness, and sharpness.

The mathematical model was then analyzed using SPSS software, performed as follows:

Regression

Descriptive Statistics

	Mean	Std. Deviation	N
Score	5.9010	2.99121	24
Loudness	26.09931667	1.063298068	24
Sharpness	2.5071708	.10122186	24

Correlations

		Score	Loudness	Sharpness
Pearson Correlation	Score	1.000	-.928	.921
	Loudness	-.928	1.000	-.998
	Sharpness	.921	-.998	1.000
Sig. (1-tailed)	Score	.	.000	.000
	Loudness	.000	.	.000
	Sharpness	.000	.000	.
N	Score	24	24	24
	Loudness	24	24	24
	Sharpness	24	24	24

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Sharpness, Loudness[b]	.	Enter

a. Dependent Variable: Score

b. All requested variables entered.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.932[a]	.869	.857	1.13299	.776

a. Predictors: (Constant), Sharpness, Loudness

b. Dependent Variable: Score

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	178.832	2	89.416	69.657	.000[b]
	Residual	26.957	21	1.284		
	Total	205.789	23			

a. Dependent Variable: Score

b. Predictors: (Constant), Sharpness, Loudness

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	281.611	184.564		1.526	.142					
	Loudness	-6.565	3.522	-2.334	-1.864	.076	-.928	-.377	-.147	.004	251.218
	Sharpness	-41.626	36.992	-1.409	-1.125	.273	.921	-.238	-.089	.004	251.218

a. Dependent Variable: Score

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions		
				(Constant)	Loudness	Sharpness
1	1	2.997	1.000	.00	.00	.00
	2	.003	30.871	.00	.00	.00
	3	1.046E-6	1692.470	1.00	1.00	1.00

a. Dependent Variable: Score

Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.6683	12.7940	5.9010	2.78843	24
Residual	-1.50098	2.66157	.00000	1.08261	24
Std. Predicted Value	-1.159	2.472	.000	1.000	24
Std. Residual	-1.325	2.349	.000	.956	24

a. Dependent Variable: Score

Fig. 13 Results of analyzing mathematical models of sound quality using SPSS software

The non-standard coefficient was brought into equation (13) to obtain the multivariate linear regression equations.

$$SQ = -6.565 \bullet Ld - 41.626 \bullet Sp + 281.611 \tag{13}$$

This multivariate linear regression equation shows that drone noise quality can be objectively described mainly by loudness and sharpness, and can achieve the goal of improving the sound of drone quality by controlling loudness and sharpness.

5 Summary and Conclusions

This paper addresses the active control method of drone noise and considers the feasibility and practical effects of combining the existing hardware of drones with the feedback active noise control (ANC) system. Through experiments, secondary noise signals were selected for the characteristics of drone noise, which partially reduces the hardware demand. Compared to traditional ANC systems, using the acoustic quality multiple regression equation replaces sound pressure level (SPL) evaluation by focusing on sound quality improvement. This led to the construction of the active sound quality control (ASQC) scheme for drones, which was validated by both simulation and subjective evaluation results.

Firstly, the effectiveness of the ASQC system was verified by subjective evaluation tests. Secondly, the correlation and influence coefficients between loudness, roughness, sharpness， fluctuation strength， A-weight SPL, and sound quality were analyzed. Through correlation analysis, multiple regression equations that can objectively describe the correlation of sound quality and psychoacoustic parameters were established, demonstrating that the psychoacoustic parameters are more suitable to describing sound quality than the A-weight SPL. There is no doubt that ASQC is an effective tool to improve the sound quality of drones when selecting the appropriate filter parameters. Given the impact of individual preferences on subjective evaluation, choosing a larger jury can improve the accuracy and stability of the results.

Finally, the implementation of ASQC technology still faces many problems with regard to drones. Compared with cars, large passenger planes, and other confined spaces, the actual effects of the system are affected by the network, hardware, and other aspects. Secondly, the improvement goal of this system is with respect to only the drone operator, which limits the applicable scenarios. However, ASQC overall provides new research ideas for improving drone noise. In the case of reducing noise in only a single frequency band, the visual perception of human drone noise will still be significantly improved. In the future, the development of electronic communication technologies and microelectronics may lead to better ASQC schemes.

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