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Jet Noise Abatement Technologies for the Republic of Korea Air Force

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Abstract

Although the noise levels of commercial jet airliners have been decreasing, the noise levels of tactical jet aircraft have stayed high as these jet fighters display high performance capabilities with powerful engines producing added thrust, and have not been able to adopt higher bypass ratio turbofan engines. Since most Republic of Korea Air Force (ROKAF) bases are located very close to large cities, the ROKAF is not only criticized as a main source of the community's annoyance with jet noise, but also has suffered from limitations to air operations and training. In addition, the South Korean government is burdened with financial compensation. Noise reduction technology will address these issues, as well as improve the advanced stealth technology for ROKAF's next generation jet fighter (KF-X).

For these reasons, ROKAF must obtain noise abatement technology with a long-term perspective. Considering the lack of knowledge about jet noise, ROKAF could learn about such technology from other countries' efforts and lessons learned. Several U.S. military and civil institutions have invested in research to develop quieter aircraft. Their research identified the main source of jet noise, and implemented novel technologies such as the chevron nozzle and plasma actuator to reduce jet noise.

In order to identify the most prospective solutions to reduce jet noise, this paper examined a variety of potential technologies with a validity check: how much each technology can reduce noise effectively; is there a negative effect to aircraft capability and safety; and are cost and time feasible. This paper, consequently, reached the conclusion that the fluidic chevrons and plasma actuator are the most appropriate recommendation for ROKAF in 2031. Obtaining quieter jet fighters, the ROKAF can fortify its combat power with few flying limitations and increased stealth capability, in addition to relieving a financial burden from the South Korean government.

Introduction

Jet noise has been an environmental problem since the advent of jet engines. The problem, however, has become more severe due to the increasing number of jet flights, more powerful jet engines needed for bigger jet fighters and encroachment of residential areas around military airbases. The Republic of Korea Air Force (ROKAF) is not an exception to such a problem because most ROKAF bases are located very close to large cities.

Non-Governmental Organizations (NGOs) and annoyed residents have insisted the best way to solve noise issues would be to move the Air Force bases to remote locations, but it would not be a feasible solution due to relocation costs and the need to remain in the appropriate strategic locations when considering preparations for a North Korean invasion. In addition, lawmakers have submitted bills requiring the prevention of and compensation for jet noise, in spite of the obvious anticipation that these bills would be a significant financial burden for the South Korean government. In response to the request of reducing jet noise, the ROKAF has limited air operations as well as pilot training around bases by instituting curfews, flight path restrictions, and other measures. Such restrictions, however, have had negative effects on air operations and pilot training.

The ROKAF, therefore, must obtain noise abatement technology in the future to relieve residents' annoyance, and to effectively and efficiently carry out critical Air Force operations and training without further limitation. After analyzing the ROKAF's and other countries' efforts and lessons learned for jet noise abatement, this paper reached the conclusion that the fluidic chevrons and plasma actuator are the most appropriate recommendation for ROKAF in 2031. Additionally, these noise abatement technologies can provide the ROKAF's next jet fighter, the KF-X, with stealth capability by reducing noise and infra-red (IR) signals of jet engines.

The ROKAF's Jet Noise Issues

Noise Prevention and Compensation bill

The South Korean Supreme court ordered the Korean government to compensate residents for their suffering due to aircraft noise, tacitly admitting the government's responsibility for jet aircraft noise at Air Force bases. The Ministry of National Defense (MND) reported total compensation for the last three years was over four hundred million (U.S.) dollars.¹

Year	2010	2011	2012	Total (M dollars)
Compensation	137.648	174.978	93.869	406.495

Table 1. Monetary compensation paid by South Korean government for noise damage

In addition to other lawsuits in process, expected to cost the South Korean government almost two hundred million dollars, both governing and opposition legislators submitted the Jet Noise Prevention and Compensation bill in August 2012 to prevent and compensate for noise damage caused by military operations. This bill states several specific compensations for communities, and facilities to improve the noise environment. According to this bill, MND has to designate and notify residents of noise zones around airbases, in addition to establishing automatic noise measurement devices and noise prevention facilities. The South Korean government has to compensate for physical, material and mental damages as well as moving and removal cost for residents who live in noise zones. The expected monetary compensation is shown in Table 2.

Year	2013	2014	2015	2016	2017	Total (M dollars)
The minimum amount	361.278	324.116	361.401	329.054	371.818	1,747.667
The maximum amount	999.539	987.391	1,050.620	1,045.280	1,116.096	5,198.926

Table 2. The expected monetary compensation according to the bill²

Pilot training restrictions

ROKAF HQ created the noise abatement program to reduce jet noise in response to increasing noise complaints, in spite of the concern it could weaken pilots' combat power and flying skills resulting from specific flight limitations. This program has required jet fighters to avoid low altitude and high speed flight around airbases; for example, tactical departures and approaches necessary to defeat adversary ambushes near an airbase in wartime. Touch-and-go exercises are crucial for new pilots, but such exercises are also limited because of the fact that they must take place near an airbase. In addition to the day-time limitation (a maximum of five passes), touch-and-go exercises are banned after 2100. This limitation could inhibit night training, and hinder ROKAF's all-weather operation capability. At the bombing range, there are similar restrictions such as altitude, the number of delivery passes and munitions, and type of bombs. Fewer delivery passes and bombs could undermine the pilots' skill and confidence.

Moreover, the ROKAF's average of total flying hours in a year has been insufficient recently. The Air Force has set 150 hours as a minimum for fighter pilots to maintain combat readiness, but average only 135 hours annually over the last six years, mainly due to ROKAF's limited budget for purchasing fuel whose price has been increasing continuously in recent years. Compared to other Air Forces' minimum flying hours set to assure pilots' combat readiness, the U.S. Air Force flew 189 hours, and the British Royal Air Force flew 210 hours³. The recent encumbrance upon ROKAF pilots' flying hours points out the ROKAF does not have further room for another limitation of pilot training as it attempts to maintain its combat readiness. It, therefore, is evident that developing noise abatement technologies for a quieter jet fighter will help the ROKAF focus on its operations and training rather than struggle to reduce the noise from fighters by limiting training and operations.

Stealth capability for KF-X

South Korea has already initiated the KF-X (Boramae) program to develop an advanced multirole fighter for the ROKAF.⁴ KF-X will develop a single-seat, twin-engine jet with stealth capabilities. The overall focus of the program is producing a 4.5th generation fighter with higher capabilities than a KF-16 class fighter.⁵ The KF-X stealth capability includes the reduction of energy emissions such as radar, IR, and acoustic noise.⁶ If South Korea develops a noise abatement capability and applies it to the KF-X program, it would complement the advanced stealth capability by reducing jet noise.

ROKAF's effort to reduce jet noise

Commercial aircraft have complied with noise reduction regulations established by the South Korean Ministry of Transportation in an effort to meet the U.S. Federal Aviation Regulations (FAR) Part 36, which is applied to the ROK as well as the U.S. The Federal Aviation Administration (FAA) established FAR Part 36 to limit the maximum noise. Aircraft manufacturers developed quieter commercial aircraft with high-bypass turbofan engines, and commercial airports established noise abatement programs.

Although military aircraft are exempt from FAR Part 36, ROKAF recognizes the necessity of reducing noise, as they are one of the government institutions responsible for citizens' physical and psychological damage resulting from military jet noise. The jet fighter, however, cannot benefit from high-bypass turbofan engines producing significant reduction in noise levels. The smaller size of military fighters as well as the requirement for afterburner capability deters military aircraft manufacturers from pursuing noise reduction. Besides, the ROKAF has not obtained any direct noise abatement technologies such as aircraft or engine design improvements. Consequently, ROKAF has focused on indirect methods: developing noise

abatement procedures, building noise barrier facilities to reduce jet noise, and pacifying annoyed citizens through local community support.

- Noise abatement procedures
 - Alter flight path to avoid residential areas during take-off and landing
 - Limit tactical departure and approach to raise altitude and reduce required thrust
 - Limit flight time and landing practice, especially at night
 - Use more simulators for pilot training
- Noise barrier facilities
 - Build a Hush house: A dome shaped building used to prevent noise from propagating during ground engine check
 - Build noise barrier fences around airbases
- Support for local community
 - Establish noise-proofing windows
 - Provide free medical check up
 - Purchase property where the noise level is too severe to live
 - Encourage public relations about ROKAF efforts

Although these noise abatement procedures and facilities are successfully used around airbases, residents have increasingly complained about jet noise and have requested to move airbases to remote areas. It is clear that these indirect solutions are not sufficient to address jet noise issues, because they do not effectively attenuate noise over a particularly large area considering the source of the noise is not stationary. For this reason, the ROKAF must develop direct noise abatement technologies that can fundamentally address jet noise by controlling the source of the jet noise.

Others' efforts to reduce jet noise

As similar noise problems have occurred in other countries, several foreign institutions and aerospace industries have already invented and developed some noise control technologies. While some technologies are already commercialized, others are still in the development or concept phase. By learning from other countries' efforts, the ROKAF can obtain a good understanding of noise control technology.

United States Air Force

The USAF has also recognized jet noise as a source of not only bad public relations between USAF and the community, but also lawsuits against the Air Force since the first day of the jet engine.⁷ In response to public protest to Congressmen and other government officials, the USAF has studied the extent of the noise problem and its effect on the community, including the plans, procedures, and devices to alleviate the noise problem.⁸ These studies identified that any noise problem is made up of three component parts: a noise source, a propagation path, and a receiver.⁹ The amount of noise that an aircraft produces is determined by the power-plant, as the jet blast from the rear of the jet engine causes most of the noise.

Jet engine suppressors - one of the earliest corrections for this problem – were first developed in 1958, when the Curtiss-Wright Company offered a noise suppressing device mounted on the engine.¹⁰ However, the USAF did not accept it because these earliest silencers hindered the efficiency of operations. For that reason, the USAF has concentrated on ground structures for noise barriers, personnel noise protectors, base plans and flight procedures. Currently, the USAF investments in engine noise abatement have been solely focused on measurement and modeling, largely for community noise that has been and remains the focus for the Air Force.

United States Navy

The U.S. Navy has few neighboring residents complain of noise compared to the U.S. Air Force, but the noise level on Navy flight decks, such as carriers and amphibious assault ships, exceeds 150 dB - the ability of current available hearing protection to maintain safe levels.¹¹ In response to hearing loss cases resulting from severe jet noise, the Office of Naval Research initiated the Jet Noise Reduction (JNR) Project as part of the Noise-Induced Hearing Loss Program in 2007.¹² This project focused more on reducing jet engine noise as excessive noise occurs during the take-off period on the decks. The Navy identified three ways (Source, Path, and Operations) to reduce jet engine noise. Compared to the high-bypass ratio (commercial) engine, noise of the low-bypass ratio (fighter) engine is mostly dominated by jet effects. This project focused on technologies that reduce jet effects by reducing the velocity of the jet (Figure 1).

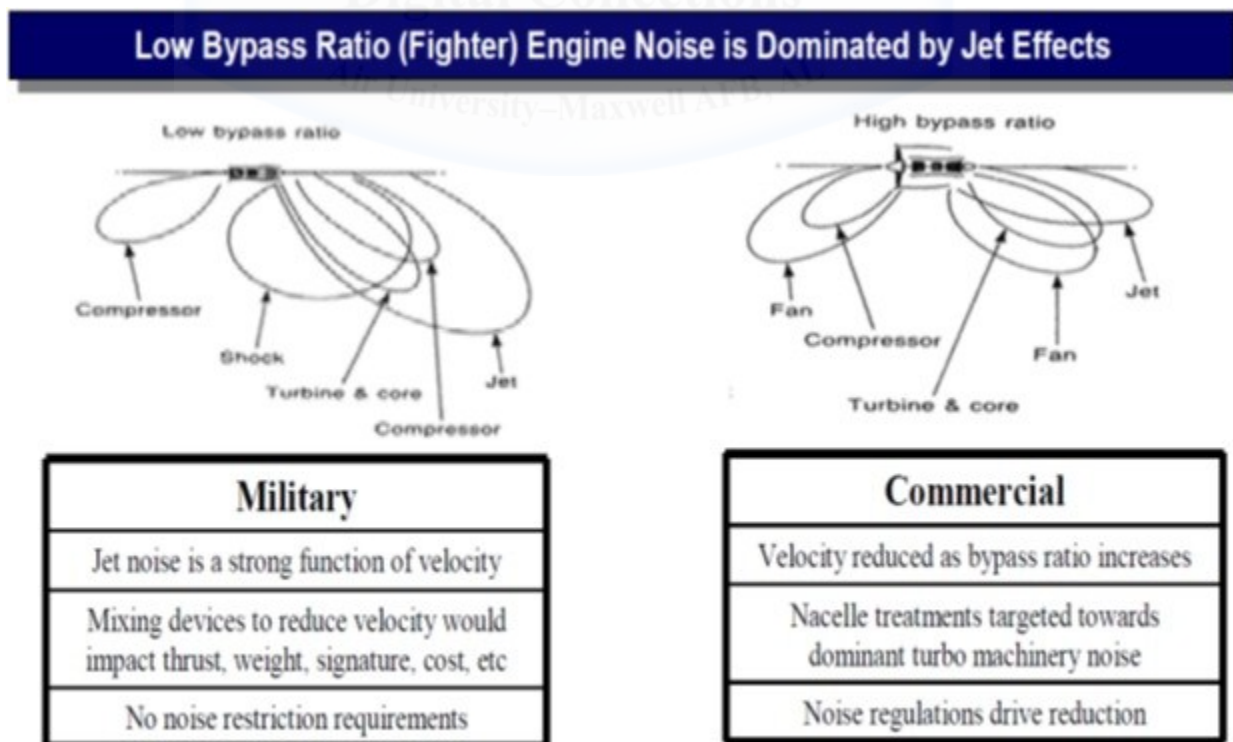


Figure 1: The main source of Fighter Engine Noise¹³

The JNR project concluded the optimal approach to reducing jet noise is to reduce the velocity of the jet. While this has worked for commercial engines, it is not a viable solution for tactical aircraft due to their high performance mission requirements. The next best approach identified is to carefully mix the exhaust stream using devices such as chevrons. Experiments confirm that the jet noise originates mostly from the end of the potential core, with secondary contributions from the mixing shear layer and shockwaves within the jet.¹⁴ Therefore, the JNR project recommended the chevron nozzle as the most feasible noise abatement technology.¹⁵

Chevrons have proven to be an effective modification to reduce jet engine noise in commercial jet engines. Chevrons incorporated on the nozzle exhaust generate a vorticity which mixes the two exhaust streams (bypass and core airflow) faster, which reduces peak velocity and hence reduces generated noise. Figure 2 shows a non-production representative F/A-18 F-404 engine undergoing tests with chevrons on the exhaust nozzle. These tests demonstrated that a 2.5 to 3 dB noise reduction was possible with minimal thrust loss.¹⁶

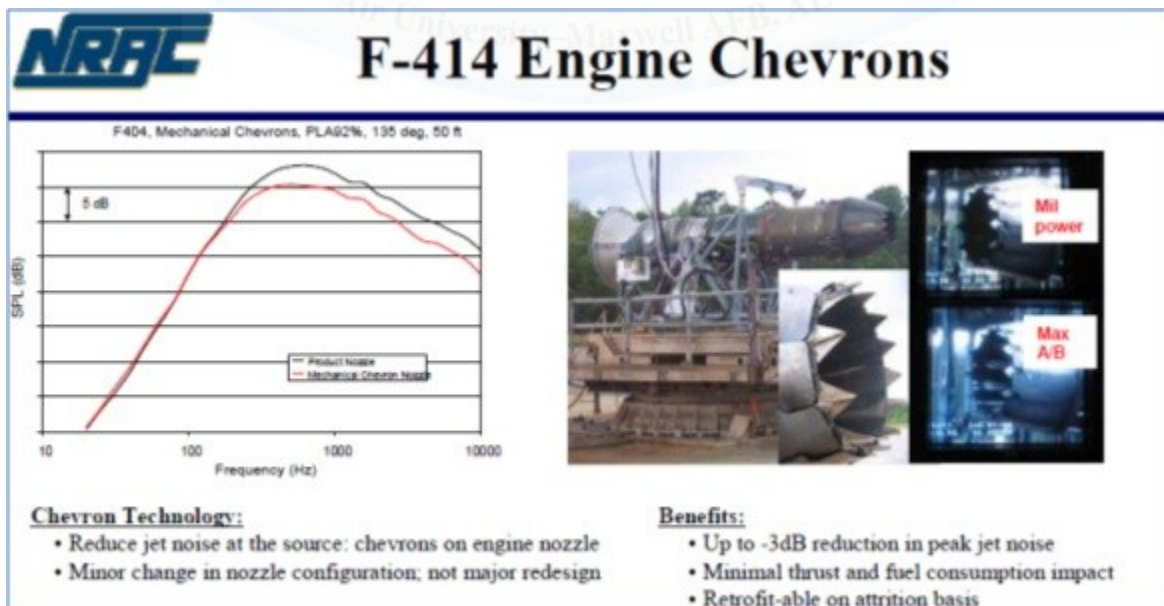


Figure 2: NAVY F-414 Engine Test with Chevron Nozzle¹⁷

National Aeronautics and Space Administration (NASA)

NASA has invested in noise reduction research since the early 1960s. In many cases, NASA research is conducted in concert with the Federal Aviation Administration (FAA), Department of Defense, the nation's engine and airframe industry and universities. Although there have been programs addressing nearly all aircraft types, a significant amount of NASA's noise research efforts in recent years has focused on conventional jet airplanes. Currently, NASA has focused on the Advanced Subsonic Transport (AST) Noise Reduction Program and the Quiet Aircraft Technology (QAT) project. The AST program began in 1994 as a seven-year effort to develop technology to reduce aircraft noise 10 dB¹⁸, and the QAT project sought to meet goals of reducing noise by 50 percent in 5 years and 75 percent in 20 years relative to 1997 technology.¹⁹ Technologies of these programs addressed aircraft and engine components including fans, exhaust nozzles, landing gear, and flap systems.²⁰

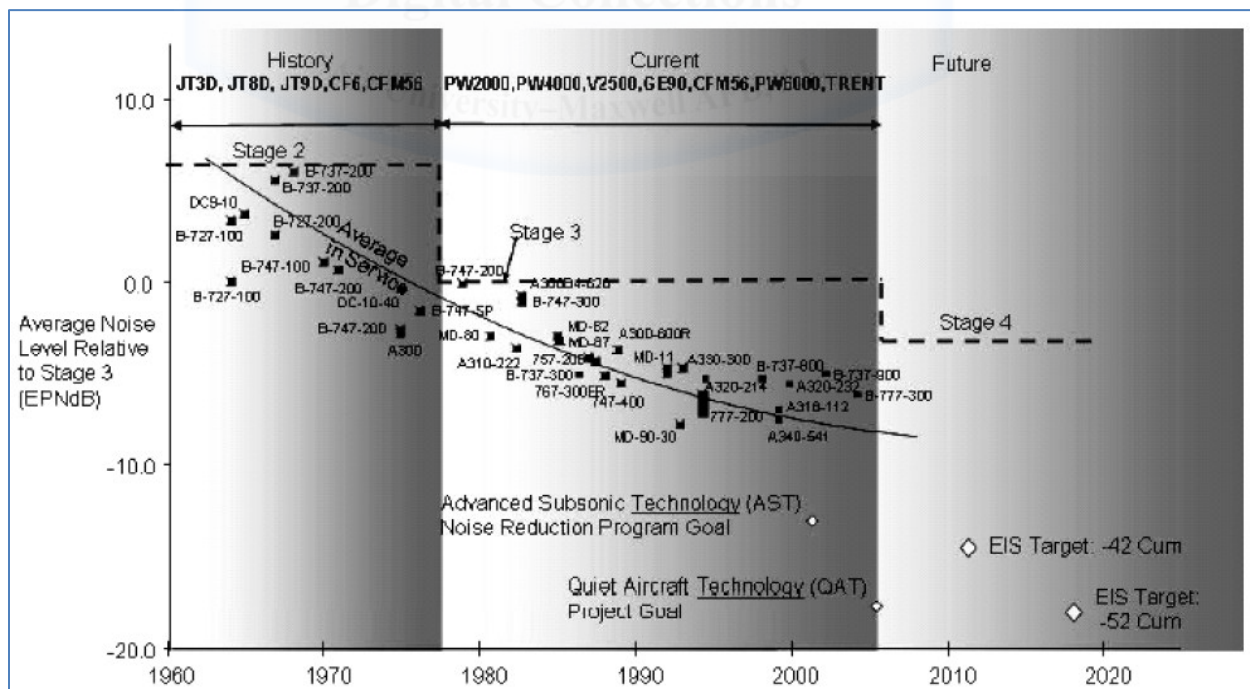


Figure 3 illustrates the progressive trend of aircraft noise reduction, as well as NASA's QAT and AST program goals. The FAA's growing noise restriction is also evident in Figure 3 as a decreasing trend line.²² Finally, even though current civil jet aircraft do not meet the goal of the NASA's AST and QAT program, considerable progress has been made developing technologies for aircraft noise reduction. As NASA learned that decreasing noise from not only the propulsion system but also the airframe was necessary, it focused on the technologies that reduce both jet engine and airframe noise. In addition to such technologies, NASA also emphasized aircraft operations around airports (Figure 4).

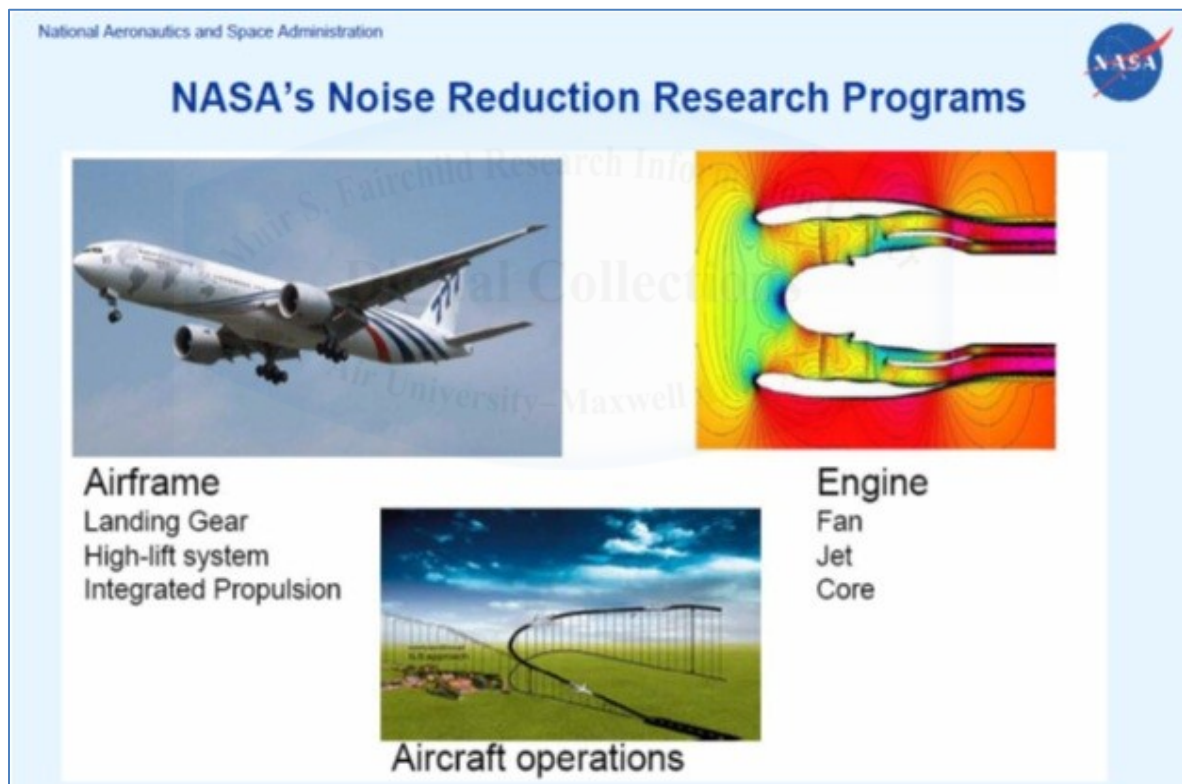


Figure 4: NASA's Noise Reduction Research Programs²³

NASA also concentrated on developing a chevron nozzle among the various types of noise-suppression devices as part of the AST program. The chevron nozzle was identified as the

most proficient method of reducing engine noise in addition to increasing the bypass ratio to lower nozzle exit velocities.²⁴

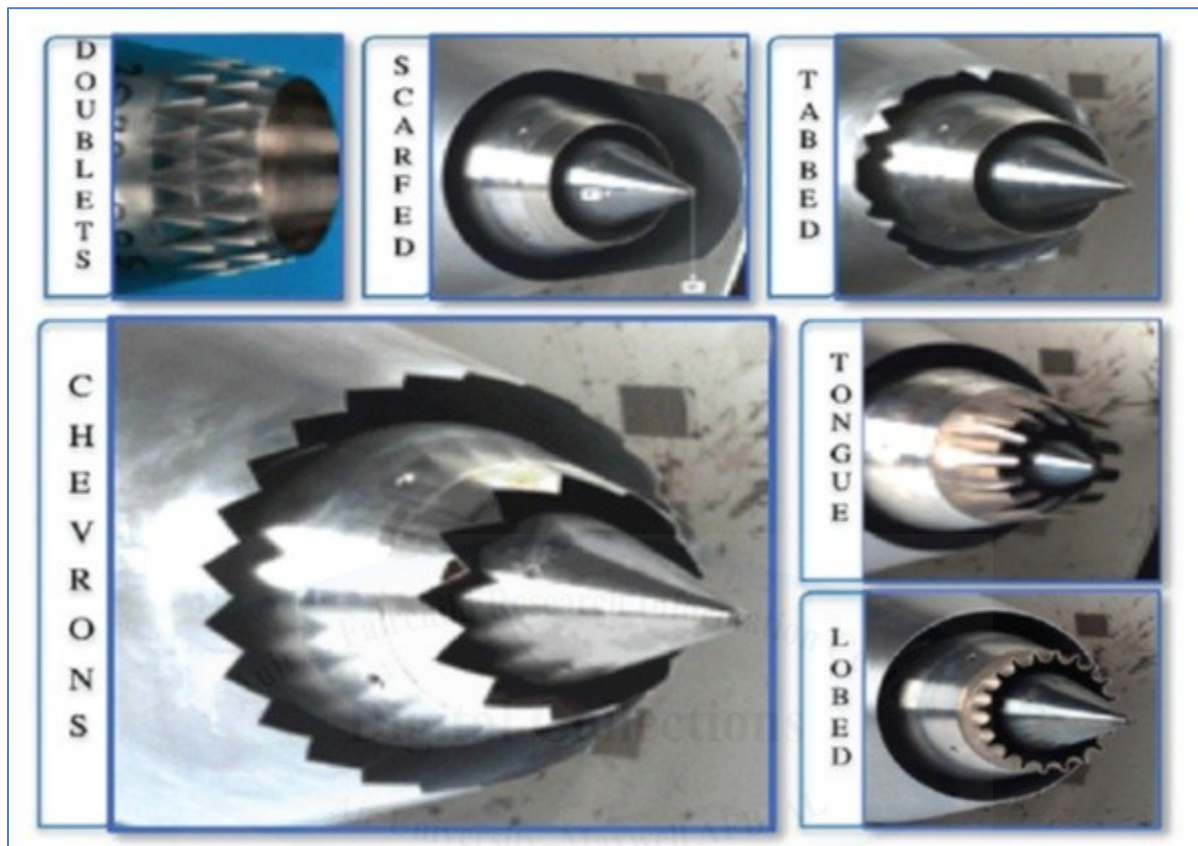


Figure 5: Various nozzle designs from the AST program²⁵

NASA invested in another noise reduction research program contracting with Boeing, Pratt & Whitney (P&W) and General Electric (GE). This research also found that the chevron nozzle was the most efficient shape to reduce noise while minimizing loss of engine thrust. This research determined “the chevron nozzle induced stream-wise vorticity along the two shear-boundary layers in the jet flow and added vorticity causes smoother mixing of the flow and reduces the rapid pressure fluctuations responsible for jet noise.”²⁶ The success of this innovative research heightened interest in chevron development for use on future business-class and commercial jet engines.²⁷ Finally, NASA and Boeing invented azimuthally varying chevrons that

reduce noise better than the existing uniform chevrons, and they installed chevron nozzles on commercial jet aircraft through the Quiet Technology Demonstrator (QTD) program.²⁸ During flight tests, uniform chevrons and variable geometry chevrons were tested and confirmed to reduce overall shock cell noise with little or no immersion into the jet flow. The reductions achieved were close to 3dBs while operating under normal power settings.²⁹



Figure 6: Azimuthally varying chevrons used in QTD2 program (NASA)³⁰

Although the chevron nozzle is the most efficient method so far to reduce jet noise, it inherently causes thrust loss during cruise conditions. Fortunately, the Boeing Company and NASA have both invested in more research to address this problem, and they have developed variable chevrons that optimize chevron immersion into the jet flow based on the flight condition by utilizing shape memory alloy (SMA) actuators to control immersion.³¹ Additionally, one more advantage of chevrons for jet fighters is the reduction of IR signatures by enhancing mixing of the engines' exhaust with cooler surrounding ambient air.³² Because most IR signatures of a jet fighter are derived from engine exhaust, chevrons could contribute to an IR stealth capability

through cooling hot exhaust quickly.

Jet-noise research has continued to evolve, and more advanced chevron-based concepts have emerged in recent years. One new innovation focuses on the replacement of mechanical chevrons with fluidic jets that simulate the metal serrations that ultimately lead to noise reduction (Figure 7). Recent NASA studies have shown that this approach offers heightened flexibility and holds promise for even greater reductions in sound. The ability to switch off the fluid injectors during cruise conditions, as well as the ability to avoid all thrust losses, makes this emerging concept highly desirable. A recent study conducted by the University of Cincinnati showed that, currently, reductions of up to 4 dB might be achievable using fluidic chevrons.³³ Alternative designs for variable chevrons (what NASA terms “active” chevrons) also continue to be of growing interest to industry.

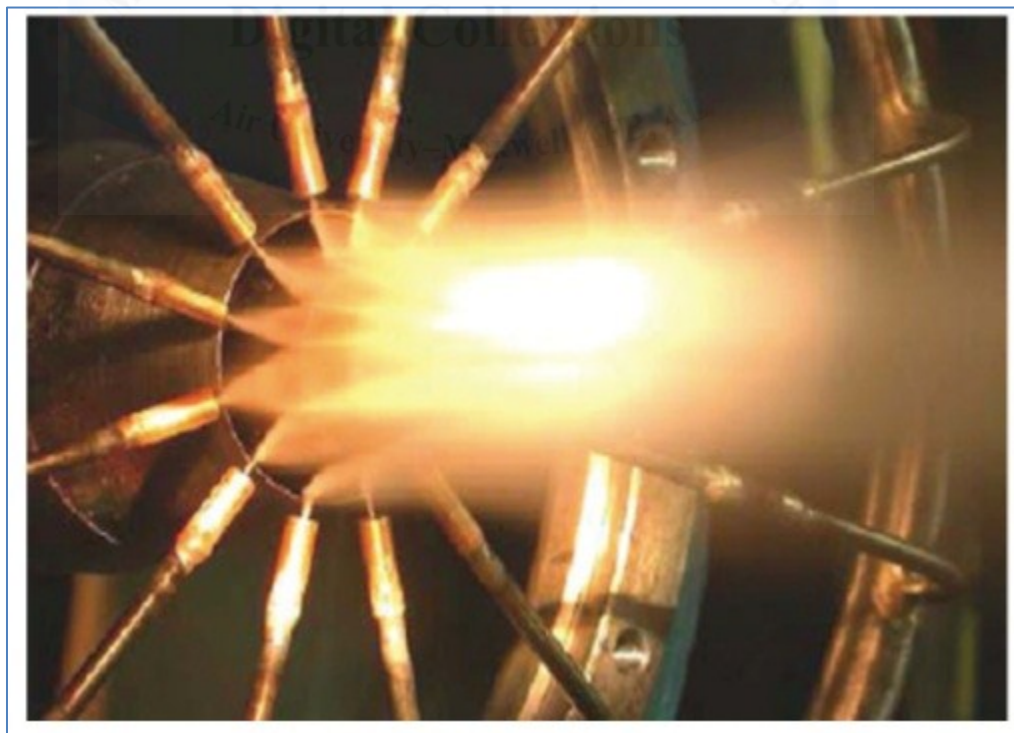


Figure 7: “Fluidic chevrons – fluid jets used to simulate mechanical chevrons (Boeing)³⁴

The Ohio State University (OSU)

OSU recently developed the Localized Arc Filament Plasma Actuators (LAFPA) device and carried out several noise control experiments with the support of many institutions such as NASA Glenn Research Center, Navy Small Business Innovation Research (SBIR), and GE.³⁵ Successfully, OSU has proven LAFPA mitigated jet noise by manipulating instabilities of the jet in not only subsonic jet (Mach 0.9) but also supersonic jet (Mach 1.3) conditions.³⁶ Plasma actuators are another novel method to control jet noise by suppressing exhaust turbulence, regarded as the main source of jet noise. The principle of using plasma actuators for noise control is to sufficiently modify the flow field in order to disrupt or to alter the mechanisms that generate flow-induced noise. This effect is achieved by placing several plasma actuators around the engine nozzles similar to the chevron nozzles. The advantages of using plasma actuators for noise control include: 1) absence of mechanical moving parts, 2) fast response, and 3) turn-on/off function depending upon need.³⁷

Localized arc filament plasma actuators (LAFPA) generate strong compression waves through rapid localized heating, which was presumed to act similarly to a sudden alternation of physical geometry. This plasma actuator could produce strong arcing that is suitable for flow and subsequent noise control applications at high speed and high “Reynolds number”³⁸. A localized arcing plasma system used for jet flow control is shown in Figure 7, where eight plasma actuators are installed along the rim of a nozzle. Each actuator consists of two electrodes, one grounded, and the other connected to a high voltage DC power supply. The circuit for only one arcing actuator is displayed for simplicity. A high voltage transistor switcher controls the activation duration for each actuator. When the transistor switcher is on, high DC voltage is applied to the connected electrode, causing a strong arc to the grounded electrode. These

localized arcing plasma actuators can be activated periodically. The duration of each actuation is generally in microsecond scale. The power consumption of each actuator is dozens of watts. The experiments showed that the jet flow and flow-induced noise can be controlled by exciting various modes with localized arcing.³⁹

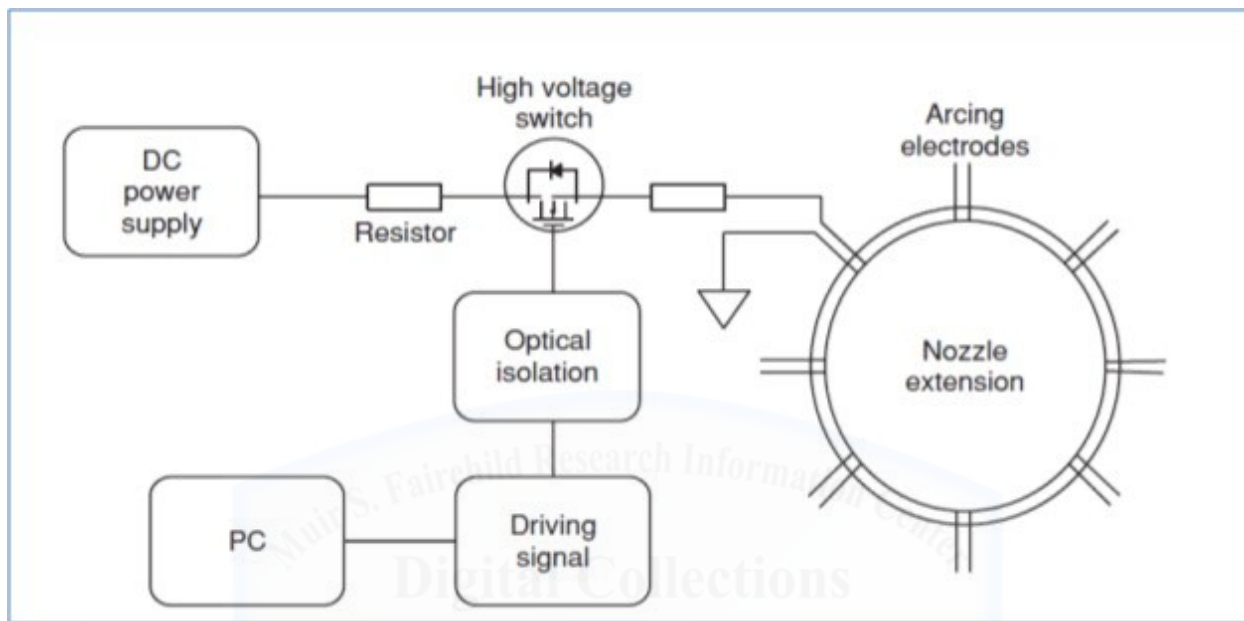


Figure 8: Schematic of a localized arcing plasma actuator system⁴⁰

The maximum reduction in the peak mixing noise is about 4 dB, greater than 3dB - the result mechanical chevrons achieved. In addition, plasma actuators could be applied to stealth aircraft technologies by reducing engine IR signatures because it allows hot exhaust to mix easily with cooler surrounding ambient air like the chevron nozzles. Reducing engine exhaust IR is considered critical for jet fighters to keep stealth aircraft from being observed by an adversary's IR detectors and missiles.

Dielectric Barrier Discharge (DBD) plasma actuators are another useful means of flow control in a variety of applications.⁴¹ The DBD actuators derive their name from the fact that a dielectric material is presented between electrodes to maintain glow discharge. Any arcing

produced between electrodes of a localized arcing actuator could be prevented in a DBD actuator by the dielectric material. As a result, glow discharges with a uniform distribution of plasma can be produced. Rather than inserting strong heat waves into the adjacent flow, DBD actuators control flow using non-thermal mechanisms. Through ionization, the DBD plasma actuators generate weakly ionized atmospheric plasma that consists of charged particles, which are moved within the coupled electric field. Through collisions between the charged particles and the ambient particles, the DBD plasma actuators act as a jet along the actuator surface. Therefore, DBD actuators facilitate the control of the vortex induced on the flaps side and trailing edge, leading edge slats, and landing gear that are the primary airframe noise sources.⁴²

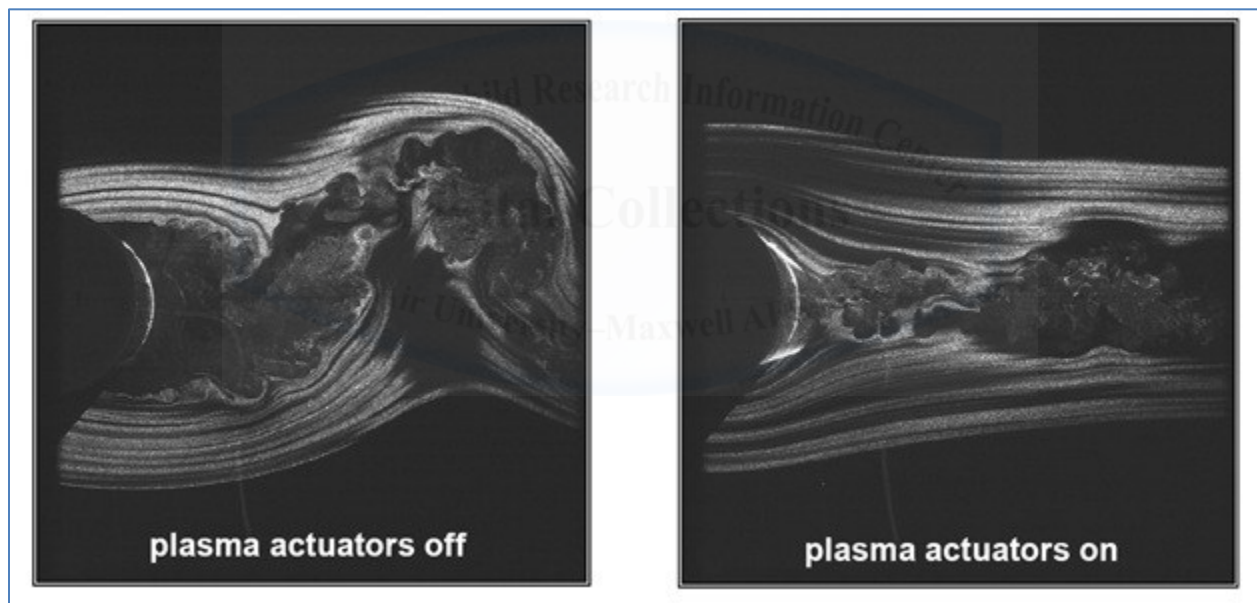


Figure 9: Dielectric barrier discharge (DBD) plasma actuator system⁴³

Possible Solutions for the ROKAF

Required amount of noise abatement

In order to identify possible solutions for the ROKAF, it is necessary to establish the amount of noise reduction required to relieve the monetary burden of the South Korean government, assure proper and sufficient pilot training to maintain and improve combat capability, and compliment the stealth capability of the KF-X. It is difficult to decide the precise required amount of noise reduction required to achieve stealth capability or eliminate community annoyance, a factor which forced the ROKAF to limit pilot training. This paper, therefore, will examine the Jet Noise Prevention and Compensation bill, which depicts the specific numerical result of measured noise as a prior reference to get a specific amount of noise reduction.

The Jet Noise Prevention and Compensation bill designates residential areas damaged by jet noise around an airbase with three zones (Zone-1, 2, 3) depending upon each noise level. For determining noise levels in this bill, the Weighted Equivalent Continuous Perceived Noise Level (WECPNL) scale formula is used.⁴⁴ WECPNL calculates the average noise over 24 hours by factoring the total noise of multiple aircraft, the frequency of occurrence and nighttime noise at a greater weight.⁴⁵

Zone-1 is the loudest, with a noise level above 95 WECPNL. Since this noise level is too severe to live in, the bill states all people and houses should be moved outside of Zone-1. This solution accounts for a great amount of financial compensation (Table 3). Therefore, if Zone-1 can be changed into Zone-2 (90~95 WECPNL) or Zone-3 (85~90 WECPNL) by decreasing jet noise by 5 WECPNL or more, then it is evident that the monetary compensation will go down considerably.

Year	2013	2014	2015	2016	2017	Total (M dollars)
10%	70,9	73,7	76,6	79,6	82,7	383,5
30%	503.169	471.366	514.172	487.7	536.462	2,512.869

Table 3. Additional required monetary budget in case 10% or 30% of residents in Zone-1 transferred⁴⁶

In addition to this bill, the South Korean Supreme Court used the 85 WECPNL for the monetary compensation of noise damage caused around military airbases. Table 4 indicates the average noise level measured around Air Force bases. Since most measurement point shows between 80 and 90 WECPNL, reducing 5 ~ 10 WECPNL can make noise level around Air Force bases lower than 85 WECPNL.

Air Force base	Measurement point	Average noise level in year (WECPNL)
Gwangju	a	79.3
	b	79.2
	c	92.2
	d	82.5
	e	85.2
	f	90.9
	g	77.8
Daegu	a	68.2
	b	78.4
	c	81.4
	d	75.6
	e	87
	f	81.8
	g	85.1

Table 4. The measured Aircraft Noise Level around Air Force bases in 2012⁴⁷

For these reasons, the best result of noise reduction will be at or above 10 WECPNL, but the goal of this paper is to achieve a minimum at or above 5WECPNL. Since the WECPNL formula is too complicated to calculate the effect of noise reduction, if assumed flying

conditions (sorties, time, and flight paths) are consistent, then the WECPNL formula can be simplified as a dB scale. Therefore, it can be restated that the goal of this paper is to achieve at least 5 dB or more noise reduction by using noise abatement technologies.

The applicable theory of noise control

The U.S. Navy has identified three ways (Source, Path, and Operations) to reduce jet noise. Since the ROKAF has already established noise abatement procedures, this paper will focus on the other two options, source control and path control.

Path control is the mitigation of noise along a certain path of its propagation. Path control is exercised through reflection and absorption and is characterized by the construction of noise barriers, noise curtains, exhaust silencers, and acoustically treated enclosures.⁴⁸ Exhaust silencers and acoustic enclosures are not recommended for jet aircraft. Although noise barriers and curtains are already being used around airbases providing interdiction of propagation, they are not effective to attenuate a noise over a particularly large area considering the source of the noise is not stationary.

Source control is the process of controlling noise production at the contributing source. Examples of source control include operation level restrictions for noisy equipment, equipment designs to reduce vibration, and the utilization of electronics in substitution for mechanics.⁴⁹ Source control is a more active and effective way to control the noise of fighter jets. Once the noise control technology works well, the noise from aircraft can be reduced regardless of the position of fighter jets. Source control, therefore, can give much more flexibility for aircraft maneuvers. For this reason, most research about noise reduction have focused on source control, and this paper recommends source control as a primary method for noise control rather than path control.

The applicable technologies for source control

Aircraft noise comes from many sources such as the fuselage, engines, landing gears, flaps and slats. As the U.S. Navy and NASA have found through their research, altering an engine is the most effective way to decrease noise in a jet fighter. Not only do engines account for the greatest amount of noise, altering the fuselage and structures such as landing gears, flaps and slats might reduce flight safety due to complications from aerodynamic characteristics. These reasons offset the benefit of reducing airframe noise achieved by altering the aircraft configuration or installing the DBD plasma actuator.

Most modern commercial and military aircraft are equipped with turbo-fan engines, which are less noisy and more fuel efficient than turbo jet engines. While commercial jet aircraft can reduce the noise better by enlarging the fan, military jet aircraft cannot achieve the same effect due to the limitation of fan size.

All research about jet engine noise found the violent turbulent mixing of exhaust gases with the atmosphere causes jet exhaust noise, and the shearing action caused by the relative speeds between the exhaust jet and the atmosphere influence that noise. When the mixing rate is accelerated, or the exhaust velocity relative to the atmosphere is reduced, a reduction in noise level can be accomplished. Changing the pattern of the exhaust jet with chevron nozzles can achieve this according to the U.S. Navy's research and NASA's QTD program.⁵⁰ Meanwhile, OSU also showed the ability to control the exhaust turbulence in noise control with the Localized Arc Filament Plasma Actuators (LAFPA) device.

Since source control is the most effective way to reduce jet noise, and controlling jet engine noise is the best way to achieve source control in jet fighters, this paper will focus on

engine noise abatement technologies: chevron nozzles - including the shape memory alloy (SMA) chevrons and the fluidic chevrons, and plasma actuators.

Examination of Chevron Nozzles and Plasma Actuators

This paper will examine these tentative technologies to learn if they will be appropriate for the ROKAF in 2031. The reason why this paper chose 2031 is, in order to reflect the budget of this technology development in the South Korean mid-term defense plan, the first step is to put this technology proposal into this year's national defense master plan (2013-2031). These two technologies will be primarily analyzed by considering their advantages and disadvantages : how much noise can each technology reduce; is there a negative effect to aircraft capability and safety; and are cost and time feasible.

Chevron Nozzles

Chevron nozzles have already proven the ability to reduce jet noise not only in the laboratories but also on civilian jet aircraft. The F/A-18 F-404 engine tests with chevrons demonstrated that a 2.5 to 3 dB noise reduction was possible with minimal thrust loss. During NASA's QTD program, flight test also demonstrated an almost 3dB reduction. In an effort to address several downfalls and improve noise reduction capability, NASA and Boeing have invested in research for advanced chevrons. The results of their research are the SMA chevron and the fluidic chevron.

This paper found several advantages. First, the mechanical chevron has proven its capability on commercial aircraft engines, and the U.S. Navy has also invested in research to develop chevrons for military jet engines. Therefore, the cost and time to develop chevrons for military jet engines would be saved by minimizing trial and error. Second, since the mechanical

chevron is inherently passively controlled with geometrical modification of nozzles, no energy is required to operate the device.⁵¹ Lastly, chevron nozzles can complement stealth capability with noise and IR reduction.

On the other hand, the mechanical chevron is not able to provide on-off function in flight. During cruise conditions, therefore, the chevrons could cause thrust loss resulting in decreased efficiency and higher fuel cost for airliners, and lower maneuver capability for military jet fighter. However, this disadvantage could be addressed with the SMA chevrons or the fluidic chevrons. Another disadvantage of chevron nozzles is noise reduction performance is less than the plasma actuators' performance - the best result chevrons achieved is 3 dB while the plasma actuator achieved 4dB. Fluidic chevrons, however, can improve the noise reduction performance.

Plasma actuator

The plasma actuator represents a novel method to control jet noise, worthy of research and development due to its remarkable advantages compared to existing noise control technologies. Recently, OSU has developed LAFPA to control jet noise, and the maximum noise reduction reached of 4 dB is the highest result among the noise reduction technologies.

There are several advantages of the plasma actuators. First, the plasma actuator is able to control noise without physical change due to the simplicity of systems and constructions, and the absence of mechanical parts. Second, the results of the tests show better performance of noise reduction than mechanical chevrons – while mechanical chevrons achieved 3 dB, plasma actuators achieved 4 dB. Third, a pilot can easily operate the plasma actuator in the cockpit in response to the necessity for stealth capability, or automatically operated based on the flight phase, and it provides quick response. Therefore, the plasma actuator does not affect engine

performance throughout all flight conditions. Lastly, plasma actuators can complement stealth capability with noise and IR control by controlling exhaust flow like chevron nozzles.

However, the plasma actuator technology is still in the laboratory, so more time and money is needed to develop it for practical use. In addition to the cost disadvantage, aircraft need additional energy generators to produce continuous glow, periodic arc, or momentary spark for flow control of plasma actuators.⁵²

Recommendation for the ROKAF Noise Abatement Technologies

This paper has considered new novel technologies that can mitigate jet exhaust noise for quieter engines in the future. The need for the ROKAF to develop quieter fighter jets is necessary for communities near air bases and air force operations. The chevron nozzle and plasma actuator both represent a useful application of noise control and additionally provide enhanced stealth capability by reducing noise and IR signal from jet exhaust with minor disadvantages.

Based on this examination, although the mechanical chevron has proven its capability through commercial jet engines, they are inappropriate for military jet engines due to the possibility of losing thrust during combat maneuvers. However, the fluidic chevrons will address this limitation with an on-off function, and provide better noise reduction than mechanical chevrons. The plasma actuator (4 dB) is closer to the established goal (5 dB) than mechanical chevrons (3 dB), and can address the problems the mechanical chevrons faced. After considering the capability of reducing noise and providing an on-off function, this paper reaches the conclusion that the fluidic chevron and plasma actuator are the most appropriate recommendations.

Although these investments in noise reduction technologies need more time and money to be applied to military jet aircraft, I think that applying these technologies for quieter engines is worth consideration for South Korea due to not only the importance of air power in modern and future warfare, but also the rights of civilians residing near Air Force bases.



End Notes

¹ http://article.joinsmsn.com/news/article/article.asp?total_id=10430444&ctg=1000

² <http://www.cjkorea.org/zbxe/865491>

³ <http://www.ywkim.co.kr/bbs/viewbody.php?code=speech&page=1&id=989&number=989&keyfield=subject&keyword=공군&category=&BoardType=&admin=>

⁴ http://www.dapa.go.kr/internet/information/opening_information/decisionprocessProc.jsp?mode=readForm&boardCode=BDINFO42&curPage=1&searchField=TITLE&searchWord=&articleSeq=11110

⁵ http://www.koreatimes.co.kr/www/news/nation/2009/03/116_41896.html

⁶ http://www.kps.or.kr/storage/webzine_uploadfiles/559_article.pdf

⁷ H. Hoggard, What can the Air Force do to alleviate the aircraft noise problem?, Air University, 1965, Pg1

⁸ Ibid.

⁹ Ibid., Pg5

¹⁰ Ibid., Pg29

¹¹ Report on Jet Engine Noise Reduction, Naval research Advisory Committee,
<http://www.dtic.mil/dtic/tr/fulltext/u2/a526482.pdf>

¹² Ibid.

¹³ Ibid., Pg6

¹⁴ Ibid., Pg12

¹⁵ Ibid., Pg14

¹⁶ Ibid.

¹⁷ Ibid.

¹⁸ NASA'S SUBSONIC JET TRANSPORT NOISE REDUCTION RESEARCH,
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040086700_2004090773.pdf

¹⁹ D.L. Huff, High-Speed Jet Noise Reduction NASA Perspective, Science and Technology Workshop for Reducing Naval Aircraft Noise, 2001

²⁰ Advancements in Aircraft Noise Abatement Technology,
http://flyquiotoak.com/_source/pdf/Tab%204g%20PDF%20links/General_National/Advancements%20in%20Aircraft%20Noise%20Technology_2006.pdf

²¹ Jayson Bulaon, Noise Suppression Methods for Turbofan Engines,
http://ae440a2009.pbworks.com/f/Noise_Suppression_Method_for_Turbofan_Engines.pdf

²² Ibid.

²³ Technologies for Aircraft Noise Reduction,
<http://naca.larc.nasa.gov/search.jsp?R=20060051741&qs=N%3D4294129243%2B4294892632%2B4294962482>

²⁴ NASA Innovation in Aeronautics, The Chevron Nozzle: A Novel Approach to Reducing Jet Noise,
http://www.aeronautics.nasa.gov/ebooks/downloads/nasa_innovation_in_aeronautics.pdf, Pg4

²⁵ Ibid., Pg5

²⁶ Ibid.

²⁷ Ibid., Pg6

²⁸ Ibid., Pg7

²⁹ Ibid., Pg9

³⁰ Ibid., Pg8

³¹ Ibid.

³² Ibid., Pg4

³³ Ibid., Pg10

³⁴ Ibid.

³⁵ Active Control of Noise in Supersonic Jets Using Plasma Actuators,
<https://mae.osu.edu/labs/gdtl/sites/gdtl.web.engadmin.ohio-state.edu/files/uploads/publications/2009/Samimy2009.pdf>

³⁶ Ibid.

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- ³⁷ Plasma actuators for noise control, International Journal of Aero-acoustics vol.9, 2010, Pg680,
<http://www.coe.pku.edu.cn/tpic/201031212560216.pdf>
- ³⁸ A dimensionless number used in fluid mechanics to indicate whether fluid flow past a body or in a duct is steady or turbulent, Oxford Dictionaries.
- ³⁹ Plasma actuators for noise control, International Journal of Aero-acoustics vol.9, 2010, Pg681,
<http://www.coe.pku.edu.cn/tpic/201031212560216.pdf>
- ⁴⁰ Ibid., Pg682.
- ⁴¹ Time-Dependent Model for Single Dielectric Barrier Discharge Plasma Actuators with Applications,
http://laurentcordier.net/seminairesLEA/archive_seminaires2009.html
- ⁴² Plasma actuators for noise control, <http://www.coe.pku.edu.cn/tpic/201031212560216.pdf>
- ⁴³ Time-Dependent Model for Single Dielectric Barrier Discharge Plasma Actuators with Applications,
http://laurentcordier.net/seminairesLEA/archive_seminaires2009.html
- ⁴⁴ $WECPNL = dB(A) + 10 \log N - 27$, where: $dB(A)$ = average noise level within 1 (one) day, measurement (24 hours).
 $N = N_1 + 3 N_2 + 10 (N_3 + N_4)$, where: N = Number of events (arrival and departure of aircraft) in 1 (one) day (24 hours). N_1 = Number of events in the period in hours 07:00 to 19:00 local time, N_2 = Number of events in the period in hours 19:00 to 22:00 local time, N_3 = Number of events in the period 22:00 in hours - 24.00 local time, N_4 = Number of events in the period 24.00 in hours - 07.00 local time
- ⁴⁵ AIRCRAFT NOISE LEVEL IMPACT AT AIRPORT AND ITS SURROUNDINGS,
http://www.uniten.edu.my/newhome/uploaded/coe_civil/mutrfc2010/003%20AIRCRAFT%20NOISE%20LEVEL%20IMPACT%20AT%20AIRPORT%20AND%20ITS%20SURROUNDINGS.pdf
- ⁴⁶ <http://www.cjkorea.org/zbxe/865491>
- ⁴⁷ http://www.noiseinfo.or.kr/data/sum_air_01.jsp?measdt=2012
- ⁴⁸ Evolution of Noise Control Technology, <http://www.noisesolutions.com/index.php/links/conference-papers>
- ⁴⁹ Ibid.
- ⁵⁰ Noise Control (Suppression), <https://engineering.purdue.edu/~propulsi/propulsion/jets/basics/noise.html>
- ⁵¹ Active Control of Noise in Supersonic Jets Using Plasma Actuators,
<https://mae.osu.edu/labs/gdtl/sites/gdtl.web.engadmin.ohio-state.edu/files/uploads/publications/2009/Samimy2009.pdf>
- ⁵² Ibid.

Bibliography

- Noise Control (Suppression)*. (1998). Retrieved February 12, 2013, from Purdue School of Aeronautics and Astronautics: <https://engineering.purdue.edu/~propulsi/propulsion/jets/basics/noise.html>
- 2, N. R. (2009, April). *Report on Jet Engine Noise Reduction*. Retrieved February 12, 2013, from Online Information for the defense community: <http://www.dtic.mil/dtic/tr/fulltext/u2/a526482.pdf>
- Advancements in Aircraft Noise*. (2006, January). Retrieved February 12, 2013, from Oakland international airport noise management: http://flyquiетоak.com/_source/pdf/Tab%20g%20PDF%20links/General_National/Advancements%20in%20Aircraft%20Noise%20Technology_2006.pdf
- Measured Aircraft Noise Information*. (2012, September). Retrieved March 31, 2013, from National Noise Information System: http://www.noiseinfo.or.kr/data/sum_air_01.jsp?measdt=2012
- Bulaon, J. (2010). *PB works*. Retrieved March 16, 2013, from Noise Suppression Methods for Turbofan Engines: http://ae440a2009.pbworks.com/f/Noise_Suppression_Method_for_Turbofan_Engines.pdf
- Clayton J. Bargsten, M. T. (2011, August). *NASA Innovation in Aeronautics*. Retrieved February 12, 2013, from National Aeronautics and Space Administration: http://www.aeronautics.nasa.gov/ebooks/downloads/nasa_innovation_in_aeronautics.pdf
- Clemans A. Powell, J. S. (2004, August). *NASA'S SUBSONIC JET TRANSPORT NOISE*. Retrieved February 12, 2013, from NASA Technical Reports Server: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040086700_2004090773.pdf
- CORKE, T. C. (2009, October 9). *Time-Dependent Model for Single Dielectric Barrier Discharge Plasma Actuators with Applications*. Retrieved February 12, 2013, from Laurent Cordier: http://laurentcordier.net/seminairesLEA/archive_seminaires2009.html
- DAPA. (2012, December 13). *The information of defense business*. Retrieved February 9, 2013, from Defense Acquisition Program Administration: http://www.dapa.go.kr/internet/information/opening_information/decisionprocessProc.jsp?mode=readForm&boardCode=BDINFO42&curPage=1&searchField=TITLE&searchWord=&articleSeq=11110
- Hoggard, H. (1965). *What can the Air Force do to alleviate the aircraft noise problem?* Montgomery: Air University.
- Huff, D. (2001). *High-Speed Jet Noise Reduction NASA Perspective*. Science and Technology Workshop for Reducing Naval Aircraft Noise.

- Huff, D. L. (2006, February 16). *Technologies for Aircraft Noise Redcuction*. Retrieved March 30, 2013, from National Aeronautics and Space Administration:
<http://naca.larc.nasa.gov/search.jsp?R=20060051741&q=N%3D4294129243%2B4294892632%2B4294962482>
- Jung, S. (2009, march 24). *Korea develops homemade stealth technology*. Retrieved february 12, 2013, from The Korea Times:
http://www.koreatimes.co.kr/www/news/nation/2009/03/116_41896.html
- Kim, C. (2012, August 6). *The prevention and compensation bill for noise damage* . Retrieved February 9, 2013, from Democratic United Party: <http://www.cjkorea.org/zbxe/865491>
- Kim, K. (2006, February). *The Korean Physical Society* . Retrieved February 12, 2013, from Stealth technology: http://www.kps.or.kr/storage/webzine_uploadfiles/559_article.pdf
- Kim, Y. (2008, October 18). *Newspaper Report*. Retrieved February 9, 2013, from Hannara Party:
<http://www.ywkim.co.kr/bbs/viewbody.php?code=speech&page=1&id=989&number=989&keyfield=subject&keyword=공군&category=&BoardType=&admin=>
- Mo Samimy, J. K.-F. (2009, June 8). *ACTIVE CONTROL OF NOISE IN SUPERSONIC JETS USING PLASMA ACTUATORS*. Retrieved February 12, 2013, from Ohio State University Department of Mechanical and Aerospace Engineering: Mo Samimy, Jinhwa Kim and Martin Kearney-Fischer
- Mose, T. L. (2009). *Evolution of Noise Control Technology*. Retrieved February 12, 2013, from Noise Solution: <http://www.noisesolutions.com/index.php/links/conference-papers>
- Park, J. (2013, January 16). Retrieved February 9, 2013, from Joongang newspaper:
http://article.joinsmsn.com/news/article/article.asp?total_id=10430444&ctg=1000
- Sakti Adji Adisasmita, A. Z. (2010, December 21). *AIRCRAFT NOISE LEVEL IMPACT AT AIRPORT AND ITS SURROUNDINGS*. Retrieved February 12, 2013, from Tenaga University:
http://www.uniten.edu.my/newhome/uploaded/coe_civil/mutrfc2010/003%20AIRCRAFT%20NOISE%20LEVEL%20IMPACT%20AT%20AIRPORT%20AND%20ITS%20SURROUNDINGS.pdf
- Xun huang, X. Z. (2010). *Plasma actuators for noise control*. Retrieved February 12, 2013, from Peking University: <http://www.coe.pku.edu.cn/tpic/201031212560216.pdf>