

Assessment of Aircraft Jet Noise Reduction Technologies

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The ubiquity of air travel attained in recent decades has exposed an unprecedented amount of people to aircraft-induced noise. As aviation noise has proven to cause significant mental and physical health disruptions, a great need exists for quieter aircraft designs should commercial aviation remain a staple of our present and future societies. Aviation noise arises from the engines and airframe of an aircraft. To this date, most aircraft noise reduction technologies have focused on reducing the sound output from the exhaust jet by facilitating rapid airflow mixing in the turbulent region downstream of the nozzle. However, aviation noise research thus far has mostly had a singular focus on a specific type of noise reduction technology. Furthermore, differences between testing methodologies of aircraft noise-related studies made cross-comparisons difficult and potentially inaccurate. To address noise emissions from subsonic commercial airliners, this paper provides an overview of various subsonic jet noise reduction methods, including passive and active ones. Then, these technologies are assessed for their noise reduction capabilities, performance penalties, and other considerations that may affect their feasibility of implementation within airliners. To alleviate the lack of standardized metrics between multiple studies, the paper will also utilize a decision matrix to objectively determine the most effective noise reduction strategies for commercial aviation in the present and near future. Chevrons and other related serrated nozzle designs were concluded to be the most optimal for current-day applications due to their relatively high noise reduction capability, manageable penalties to thrust, and high practicality. Microjet injection strategies, meanwhile, were predicted to hold a promising future alongside serrated nozzles due to their ability to incur no significant performance penalties.

Introduction

Since their invention in the 20th century, commercial airliners have become irreplaceable assets of modern-day societies. However, airliners are not without drawbacks, one of which is their noise output. Traditionally, aircraft noise has been associated with its great annoyance that outclasses road noise, even at the same amplitude¹. Unfortunately, aircraft noise has also been found to cause numerous detrimental health effects by several post-21st century research articles. For instance, chronic exposure to aircraft noise increases blood pressure and heart rate² across all ages³ and thus increases the chances of hypertension⁴, strokes⁵, and other heart-related diseases. Among children, chronic aircraft noise exposure from airports has been consistently found to delay reading comprehension development among children⁶ at school⁷ and even while at home⁸. Indirectly combating these issues by airport relocation is very limiting, as an airport's proximity to cities and other areas of interest would ultimately need to be sacrificed. Thus, reducing aircraft noise output from its source remains a far more appealing choice as the existing infrastructure would neither be hampered nor face additional challenges for future expansions.

However, aviation noise reduction technologies face numerous challenges to mass adoption. Popular methods such as serrated nozzles alter airflow around aircraft engines. However, this comes at the cost of aerodynamic efficiency. As most noise

reduction technologies inherently increase the complexity and cost of passenger planes, they become a dubious investment among most airliners. Thus, this paper will provide insight into aircraft noise reduction technologies that best balance their effectiveness with the aforementioned downsides in the next several sections.

To accomplish this, the paper will first introduce the basic mechanics of aircraft noise and set forth criteria for evaluating jet noise and methods of reducing it. Secondly, the paper will provide subsections discussing the unique characteristics of each noise reduction technology. Then, the paper will introduce a decision matrix that assists in cross-comparisons between dissimilar noise reduction technologies with a comprehensive scoring system. Finally, the paper will draw conclusions based on the decision matrix and recommend optimal noise reduction technologies for the future.

Aircraft Noise

Aircraft noise can originate from either the jet engines or airframes. Of these two, airframe-generated noise remains more difficult to reduce as it is specific to the particular design of the plane and its performance characteristics⁹. Thus, attempts at reducing the noise from jet engines yield much more value for being broadly applicable to many different aircraft.

Turbofan engines, a ubiquity among airliners of today, have five major components to the engine: the fan, the compressor, the combustor, the turbine, and the exhaust nozzle. The fans and exhaust jets produce the most noise within modern airliners under subsonic operational conditions¹⁰. This paper will focus on strategies to minimize noise from the exhaust jet of subsonic aircraft and assess their applicability for current and future aircraft designs.

Jet noise occurs when the hotter, faster-flowing exhaust jet meets the cooler, slower air traveling around the engine. As the two streams of air mix, a shear layer forms and brings about swirls of turbulent air that contribute to the broadband noise output of the aircraft. Reducing jet noise usually involves accelerating the mixing of the two streams or reducing the jet exhaust velocity. However, reducing exhaust velocity will reduce the mass flow rate of the engine and thus thrust, so many noise control strategies have been found to facilitate faster airflow mixing. When considering modern airliner turbofan engines, it is also imperative to study the relationship between an engine's noise and its bypass ratio (β). In turbofans, bypass air enters the engine inlet but does not enter the turbine core where the combustion occurs. Instead, this air travels through the length of the engine from the thrust provided by the fan. Thus, bypass ratio refers to the ratio between the mass flow rate of bypassing air and the air traveling through the turbine core. Thus, if an engine had a bypass ratio of 2 ($\beta = 2$), only a third of the air coming into the engine inlet would enter the turbine core.

By design, higher bypass ratio engines increase fuel efficiency while reducing jet exhaust velocity. Thus, if there were two otherwise identically-performing engines, the one with a higher bypass ratio would produce lower jet noise due to the lower exhaust velocity. However, higher bypass ratio engines tend to emit more tonal noise from the fan than broadband noise from the exhaust jet¹¹.

Jet Noise Evaluation Criteria

Literature Review Methodology

A comprehensive literature review was done to understand a multitude of jet noise reduction techniques. Of the articles studied, special consideration was given to those containing experimental data. To ensure the use of relevant and up-to-date data, only articles published in and after 1995 were studied. This cutoff was chosen to illustrate the aftermath of NASA's Advanced Subsonic Technology (AST) Program that validated the noise-dampening effects of certain prototype aircraft engine nozzle modifications by General Electric and Pratt & Whitney.

When studying aviation noise, it is imperative that all measurements cater to how it is perceived by human hearing. For instance, a simple average decibel reading would not be able to capture humans' greater sensitivity toward frequencies

of around 2 to 5kHz. Thus, nearly all evaluations of jet noise reduction methods presented in this paper use measurements of effective perceived noise level (EPNL) in the unit of EPNdB. EPNL indicates how loud an aircraft is during an overhead fly-by where the overall loudness, duration of noise, and human perception of sound are all considered. Thus, EPNL measures are highly applicable to real-world conditions. When EPNL data cannot be retrieved, overall sound pressure level (OASPL) measurements were used as a substitute. OASPL measurements are weighted based on human hearing perception, making them a viable alternative to EPNL in evaluating technologies never tested aboard aircraft. To further reduce inconsistencies, only jet engines with a bypass ratio of 5 ($\beta = 5$) operating in sub-sonic conditions will be considered in the evaluation as this would control for baseline noise characteristics. Despite the ability to reduce jet noise using increased bypass ratios, this method will not be included in the paper due to the additional considerations for engine dimensions, mass¹², and increased production of fan noise. Additionally, modern jet airliners are following the trend of incorporating ever-larger bypass ratios on their newer engines. Thus, basing this study around a high bypass ratio of 5 would produce results that are far more applicable to jet engines of today, which often match or exceed such a threshold.

Decision Matrix Scoring

All modifications to minimize aircraft jet noise carry unique characteristics and design considerations that may affect their value in the real world. Thus, a comprehensive comparison that considers subsonic noise reduction capabilities, performance penalty, and practicality of each technology will be used. As a result, metrics discussed in the literature review section will be organized into a decision matrix to approximate the real-world value each noise reduction method provides.

The decision matrix will have three categories: subsonic noise reduction, performance, and practicality (Table 1). Both the subsonic noise reduction and performance categories will use the data from the literature review rounded to the nearest dB and nearest percent change, respectively. The subsonic noise reduction category will be directly based on EPNL metrics, where every 1dB decrease in noise grants an additional point. Where EPNL metrics are unavailable (such as when the modified engines were not tested on aircraft), OASPL measures will be used instead. Should a noise reduction method turn out to increase the noise output instead, it will be disqualified immediately and denoted "DQ" for all other sections.

The performance penalty category will also use a numeric scale, where every 1% decrease in the mass flow rate of the engine results in a 1-point subtraction in the category. If mass flow rate data is unavailable, other measures, such as penalties in the maximum takeoff weight and range penalty, will be compounded to supplement such a metric. While based less

Table 1: Rubric for Decision matrix used to assess aircraft noise reduction methods

| Type | Subsonic Noise Reduction | Performance | Practicality |
|---------|--------------------------|-------------------|-----------------|
| Scoring | +1pt/-1EPNdB* | -1pt/-1% Thrust** | See Section 3.2 |
| Weight | 0.4 | 0.4 | 0.2 |

on numeric scales, a measure of practicality serves a crucial role in applying the benefits and downfalls of certain noise-reducing technologies to the real world. Specific criteria will reward or penalize a noise reduction method depending on how easy or difficult it is for airliners to implement into their fleets. These criteria will penalize scenarios where the benefits of "Subsonic Noise Reduction" are limited to situations that require specific aircraft or engines for optimal results. Conversely, bonus points will be rewarded if noise reduction capabilities can be achieved in a wide selection of aircraft thanks to retrofit solutions. Such criteria for practicality scoring are:

- -1pt if a noise reduction method's benefit greatly varies among different aircraft
- -1pt if a noise reduction method's benefit is significantly lesser in newer aircraft or is most beneficial for far-future technologies
- -1pt if a noise reduction method significantly increases engine dimensions or mass
- -1pt if a noise reduction method incurs significant aerodynamic penalties
- -1pt if active monitoring and adjustments are required to yield noise reduction
- -3pt if a noise reduction method requires significant engine internal redesigns to yield benefits
- +1.5pt if a noise reduction method is a retrofit

Additionally, an initial score of 5 will be given to all noise reduction technologies. This is because this practicality scoring system is mainly designed to penalize shortcomings instead of rewarding the lack thereof. Therefore, the initial score would balance out the otherwise overwhelmingly negative-biased category. No advantages or disadvantages will be present as all noise reduction technologies receive this initial score. Notably, technologies that require internal engine redesigns are heavily penalized while retrofit solutions are favored. This reflects the current state of most airliners that possess aircraft that largely lack significant forms of noise reduction technologies in their engines. A retrofit solution would give them appreciable outcomes for much lower costs than replacing their fleet with newer planes. On the contrary, implementing technologies that require internal engine redesigns would be extremely costly. Aircraft would need to have their engines torn down and rebuilt

from the ground up or acquire new engines entirely to implement compressor or turbine-specific modifications.

Once the scores of each category are calculated, a final evaluation score will be calculated using a weighted sum. The subsonic noise reduction, performance, and practicality categories will each have a 40%, 40%, and 20% weight, respectively. These weights allow foreseeing near-future subsonic noise reduction technologies thanks to the slightly de-emphasized practicality consideration. As a result, technologies that may be too complicated to be implemented in commercial airliners today receive a lesser penalty under the assumption that the technology would mature over time. Despite that, the equal weighting of noise reduction and performance ensures that the need for silent-yet-more-performant aircraft is equally addressed. Overall, these weights are structured to penalize noise reduction technologies that are still too costly to implement, but they are also set to favor borderline technologies that may become especially useful soon. After all, airliners are designed to last for a few decades, and so they must be equipped with technologies that will still be relevant in those times.

Literature Review

Six noise-reduction strategies have been assessed, one of which is an active noise control method. The remaining five are passive methods.

Passive Noise Control

All passive noise control methods are similar in that no additional moving parts are used to modify the aircraft's exhaust jet. Thus, passive strategies permanently modify the engine while generally being much more simplistic and requiring less maintenance than their active counterparts

Tabbed Nozzles and Chevrons

Tabbed nozzles and chevrons use small protrusions at the back of the engine that help facilitate faster mixing of the exhaust jet with the surrounding air¹². The difference between the two is that tabbed nozzles utilize small rectangular tabs, while chevrons and other serrated nozzles use triangular serrations. Both tabbed nozzles and chevrons reduce low-frequency noise content from the exhaust jet but may increase the output of high-frequency noise in places where the exhaust directly contacts the protrusions, particularly the rectangular ones used by tabbed nozzles. This high-frequency noise content is more

easily absorbed by the atmosphere, but for tabbed nozzles, their excessive generation of high-frequency noise amounts to a negligible reduction in overall perceived noise output¹³. As both tabbed and serrated nozzles disrupt the exhaust flow to facilitate faster mixing, additional consideration should be given to the thrust loss that comes with these technologies. Here, rectangular protrusions used in tabbed nozzles penetrate the exhaust stream more sharply and come with a greater penalty in performance¹³. For this reason, triangular serrated nozzles, or chevrons, stand out as the more attractive nozzle modification for current and future generations of aircraft¹³. Older generation aircraft saw mixed results from chevrons, but the impact remained negligible and never produced any additional noise in meaningful quantities¹⁴. When designing chevrons, there may be multiple aspects to consider, such as the size, count, and angle of exhaust jet penetration. One large-scale experiment from NASA crowned a particular design variant (as seen in Fig. 1) with irregularly placed and angled triangular serrations to produce 3EPNdB less noise¹⁵. Other studies also indicate a similar level of noise reduction¹². A follow-up study also revealed that the nozzle produced a modest 0.99% decrease in thrust¹⁶.

Precision Medicine Treatments in Breast Cancer

Based on the molecular profile, there are three main subtypes of breast cancer: estrogen receptor positive (ER+) breast cancer, human epidermal growth factor receptor 2 positive (HER2+) breast cancer, and triple negative breast cancer (TNBC)^{17, 18, 19}.

Mixer Nozzles

Mixer nozzles utilize a similar noise reduction strategy to that of tabbed and serrated nozzles but with lobular protrusions as seen in Fig. 2 instead. The aforementioned study from NASA also tested these types of nozzles and found that the benefits were no more than a 1EPNdB reduction¹⁵. The primary reason for this shortcoming was that mixer nozzles yield greater benefits with higher exit jet velocities. Where jet exit velocities were sufficiently low (as is the case for low-throttle conditions with high bypass-ratio engines), the nozzle saw produced negligible changes to EPNL metrics due to the increased production of high-frequency noise overshadowing much of the reduction brought to the low-frequency components¹⁵. Another study from NASA also revealed that thrust deficit from mixer nozzles was about 1.867% for a similar design, a number that decreased with designs incorporating fewer lobes at the expense of noise reduction effectiveness¹⁷.

Corrugated Nozzle Hush Kits

Hush kits (as seen in Fig. 3) are retrofittable noise reduction devices commonly used by older, louder aircraft. These structures act as extensions of the engine, and the vast majority

provide a nozzle that resembles that of mixer nozzles. However, their noise reduction potential is greater than that of mixer nozzles at 2.5EPNdB¹⁸, most likely due to their larger lobes reaching all the way down the exhaust stream's center instead of just the outer boundary. This trend also holds true for hush kits' performance penalties, as they brought about a 2% loss in range¹⁹ accompanied by 0.5% lower maximum take-off weights²⁰. This is greater than that of mixer nozzles. Additionally, considerations for excess mass and drag should also be necessary for hush kits, as such devices are extensions to the stock engine nozzles, not replacements.

Distributed Nozzles

Distributed nozzles (as seen in Fig. 4) take a fundamentally different approach to facilitate faster mixing of the jet. Instead of helping one large plume of exhaust to mix with the air, distributed nozzles split it into multiple different streams that can much more readily mix with the air. These smaller nozzles produce significantly less low-frequency noise while the atmosphere easily attenuates the increased amount of high-frequency noise they generate. In fact, the 10kHz peaks from the distributed nozzle tested by the AIAA are attenuated to such an extent that EPNL readings essentially start ignoring them²¹. Unfortunately, distributed nozzles have only recently emerged among researchers, and testing data on these nozzles fitted on actual aircraft is very limited. Thus, most data exists as OASPL readings from distributed nozzles mounted

to loose engines. Even so, the noise reduction aspect has been promising with improvements of up to 10dB OASPL but at the hefty cost of a 10% thrust penalty²¹. However, distributed nozzles still have the potential to hold a promising future, as they could give birth to new aircraft designs that distribute the jet exhaust throughout various locations in the airframe to even further reduce noise with less of a penalty to thrust²³. Such designs, however, will most likely come after distributed nozzles gain popularity, which remains a distant prospect from today.

Scarfed Fan Nozzles

Scarfed fan nozzles (as seen in Fig. 5) take another approach to noise reduction by attempting to shield the jet exhaust at a specific angle and redirecting it to another. For instance, such a nozzle could reflect much of the noise that would have traveled down to residential areas into the sky. This shielding is particularly effective towards higher-frequency noise content, making scarfed nozzles potentially enticing for use cases with other nozzles that produce greater high-frequency noise content. NASA carried out one such experiment where a half-mixer half-scarfed nozzle was built to be compared with other full mixer nozzles¹⁵. Unfortunately, this nozzle failed to achieve its ultimate purpose, as it increased the noise output by about 2EPNdB¹⁵ over a baseline nozzle. This downfall is mainly



Figure 1: NASA's 3T24B serrated nozzle that consists of a 24-flipper-tabbed core nozzle and a base- line fan Nozzle¹⁵



Figure 2: NASA's 3FmB mixer nozzle that consists of a Full-Mixer Core Nozzle and a Baseline Fan Nozzle¹⁵



Figure 3: A hush kit Installed on a Rolls Royce Conway Mk508 engine used on the Boeing 707-420²²

attributed to scarfed fan nozzles' inability to deflect lower frequency noises, the types of noise that have the greatest potential to travel farther. Thus, scarfed fan nozzles serve to demonstrate the need to focus reductions in lower-frequency

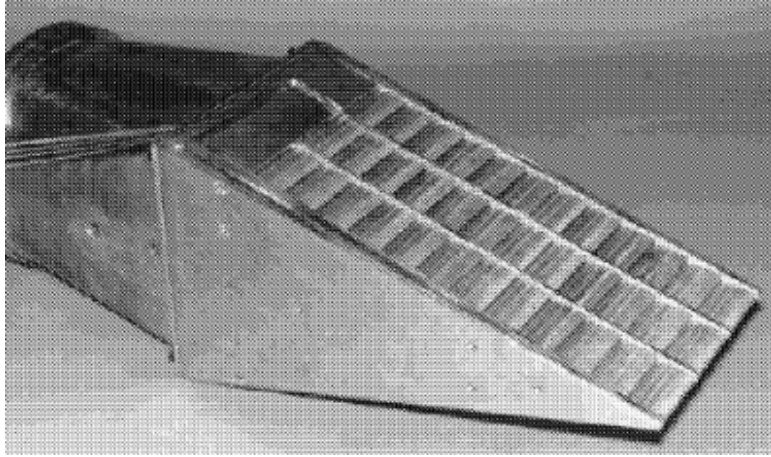


Figure 4: A prototype distributed nozzle tested by the AIAA²¹

noise over an equivalent higher-frequency one.

Active Noise Control

Active noise control directly manipulates the noise source, usually relying on moving components near the exhaust or on-the-fly modifications to the combustion process. Due to these added complexities, however, active noise control methods were mostly ignored until recent years²⁴. However, one of active noise control's greatest benefits resides in the ability to disable it when not necessary, such as when aircraft are at their cruising altitude far away from cities. Given how planes spend the vast majority of their time at cruising altitude, active noise reduction methods may be utilized to incur no tangible performance compromises while providing all the benefits during takeoffs and landings.

Microjet Injection

Microjet injection (as seen in Fig. 6) relies on specific injectors to expel puffs of air or other fluids at the nozzle exit to dissipate the shear layer in a similar fashion to passive noise control methods. These structures are usually internal to the engine, so they may not contribute to increased drag in a way passive control structures can²⁴. Microjet injection can have numerous implementations that vary depending on the substances injected and the injection method used. One method involves injecting water that amounts to less than 1% mass flow reduction with a 1EPNdB decrease in noise²⁴. At supersonic speeds, noise levels saw improvements of up to 13dB OASPL with a 1.5% reduction to the jet, but this metric holds little value for airliners as there are no supersonic jet airliners currently operational¹³. Furthermore, the ideal configuration with the greatest noise reduction requires an active feedback loop system in which the injectors vary their operations according to the sensor readings from the exhaust stream¹³, increasing the

complexity for commercially viable microjet injection solutions.

Decision Matrix Evaluation

All scores listed below can be found on Table 2. Tabbed nozzles and chevrons considerably led ahead with a final score of 1.6. Microjet injection technology and distributed nozzles trailed behind with a final score of 0.6, followed by hush kits at 0.5. Mixer nozzles received a final score of 0.2, while scarfed fan nozzles were disqualified entirely.

Tabbed/Chevron Nozzles

Chevrons received a score of 3 in the subsonic noise reduction category for bringing about a 3EP- NdB decrease in noise output¹⁵. In the performance category, chevrons received a score of -1 for bringing about a 0.99% loss in thrust^{16,17}. Lastly, chevrons received a practicality score of 4. The reasons are as follows: From a base score of 5, chevrons received a 1-point deduction for having diminished benefits on older aircraft¹⁴. As a result, chevrons received a final score of 1.6 by the equation: $(+3)0.4 + (-1)0.4 + (+4)0.2 = 1.6$.

Mixer Nozzles

Mixer nozzles received a score of 1 in the subsonic noise reduction category for the 1EPNdB decrease in noise output they provide¹⁵. They received a performance score of -2 due to the 1.867% penalty in the mass flow rate of the engines tested¹⁷. Mixer nozzles received a practicality score of 3 for the following reasons: From a base score of 5, mixer nozzles received two 1-point deductions as they display diminishing benefits for current-day aircraft with high bypass ratio engines¹⁴ and for future aircraft¹⁰ that would sport even higher bypass



Figure 5: NASA's 3BS scarfed-fan nozzle that consists of a scarfed fan nozzle and a baseline core nozzle¹⁵

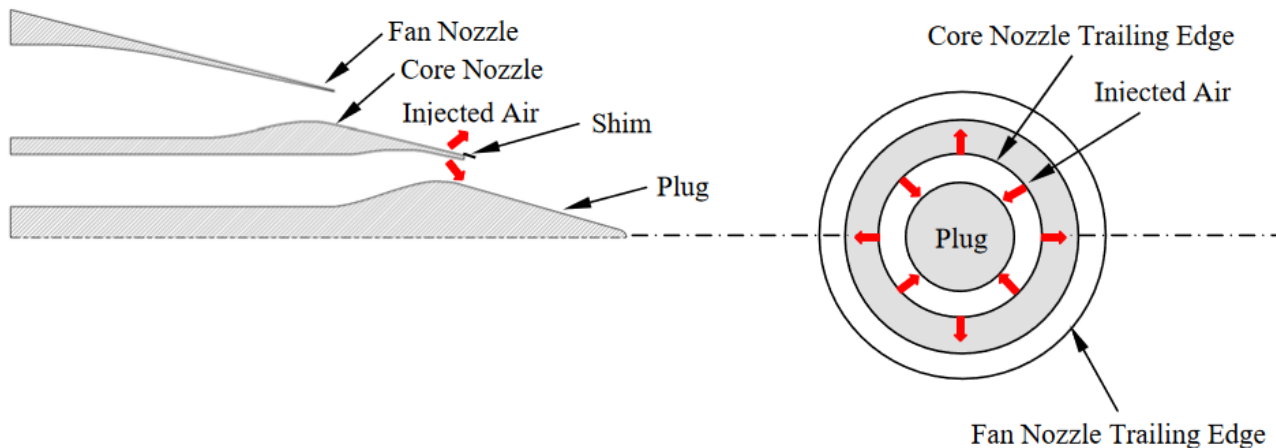


Figure 6: NASA's schematic of their microjet injection nozzle²⁵

ratio engines¹⁵. This grants mixer nozzles a final score of 0.2 as per the weighted sum: $(+1)0.4 + (-2)0.4 + (+3)0.2 = 0.2$.

Hush Kits

Hush kits received a score of 3 in the subsonic noise reduction category for the 2.5EPNdB decrease in noise output¹⁸. They received a performance score of -3 due to the combination of a 2in range¹⁹ and 0.5% reduction in maximum takeoff weight²⁰. The aggregated value of -2.5% was rounded to -3% for this calculation. Finally, hush kits received a practicality score of 2.5. The reasons are as follows: From the base score of 5, hush kits received four 1-point deductions for having diminished benefit for current aircraft with high bypass ratio engines¹⁴, diminishing returns for future aircraft¹⁰ with even higher bypass ratio engines¹⁵, inevitably increasing engine dimensions and mass, and incurring aerodynamic penalties. However, they received a 1.5-point bonus to the category for being a retrofit solution. These factors all surmount to a final score of 0.5 under

the following weighted-sum calculation: $(+3)0.4 + (-3)0.4 + (+2.5)0.2 = 0.5$.

Distributed Nozzles

Distributed nozzles received a score of 10 for the subsonic noise reduction category by bringing about a massive 10dB OASPL decrease to noise output²¹. This is followed up by a performance score of -10 due to the large 10% thrust penalty they bring²¹. Distributed nozzles also received a practicality score of 3. The reasons are: From a base score of 5, distributed nozzles received two 1-point deductions due to the extreme thrust penalty that would hamper their suitability in most aircraft²³ and the fact that only radical supersonic transports of the far-future will be able to feasibly benefit from the entirely new designs incorporating multiple jet distribution²³ structures. This leads to a final score of 0.6 from the following calculations: $(+10)0.4 + (-10)0.4 + (+3)0.2 = 0.6$.

Table 2: Decision matrix for aircraft noise reduction methods

| Type | Subsonic Noise Reduction | Performance | Practicality | Final Score |
|---------------------------|--------------------------|-------------|--------------|-------------|
| Tabbed Nozzles & Chevrons | 3 | -1 | 4 | 1.6 |
| Mixer Nozzles | 1 | -2 | 3 | 0.2 |
| Hush Kits | 3 | -3 | 2.5 | 0.5 |
| Distributed Nozzles | 10 | -10 | 3 | 0.6 |
| Scarfed Fan Nozzles | -2 | DQ | DQ | DQ |
| Microjet Injection | 1 | 0 | 1 | 0.6 |

Scarfed Fan Nozzles

Scarfed fan nozzles received a score of -2 for the subsonic noise reduction category for increasing noise output by 2EPNdB¹⁵. This subsequently disqualified them from any other assessments. Scarfed fan nozzles will be treated as the lowest-scoring of all other noise reduction technologies.

Microjet Injection

Microjet injection received a subsonic noise reduction score of 1 for bringing about a 1EPNdB decrease in noise output²⁴. While microjet injectors have been found to cause a 1% mass flow rate reduction in use²⁴, the ability to disable them¹¹ for the vast majority of the flight where the noise output is less of a concern grants microjets a score of 0 on the performance category. Microjet injection technology also earned a practicality score of 1 for the following reasons: From a base score of 5, the technology lost one point for requiring active monitoring and continual adjustments to the injection patterns to be effective¹³ and a further three for requiring non-superficial engine redesigns to be accommodated²⁵. These all lead to a final score of 0.6 ((+1)0.4 + (0)0.4 + (+1)0.2 = 0.6).

Discussion

The decision matrix reveals that chevrons and other forms of serrated nozzles have an outstanding lead over other technologies. This is because of their high noise reduction capabilities and practicality for modern applications without much of a performance penalty. However, chevrons still have some drawbacks, as their ineffectiveness in older generation aircraft and slight permanent reduction in engine performance leave room for improvement that an improved version or other auxiliary technologies would need to fill. Even so, the many advantages of chevrons would most likely prompt a quieter future in which they would be widely used.

The second place is shared by distributed nozzles and microjet injection, methods that promise radical shifts to aircraft design in the future. After all, distributed nozzles yield the greatest noise reduction of all methods evaluated. Unfortunately, they are relatively new and have seen little operational use in commercial

airliners, and the large performance penalty might prove to be too costly. As for microjet injection, its main advantage is that it is the sole active noise control method evaluated. While its benefits are relatively minor under subsonic conditions, the performance penalty can effectively be ignored, as these systems would only need to be active during takeoffs and landings where aircraft noise imposes the largest disruption to human lives. Not only that, microjet injection can be used in conjunction with other noise reduction methods such as chevrons, boosting the joint effectiveness even further¹¹. This leaves the technology's added complexities as its main remaining weakness, but as microjet injection technologies mature, they may soon become viable for use in the real world. Up next are hush kits that scored only marginally less than distributed nozzles and microjet injection. Unfortunately, this retrofit solution's versatility diminishes daily as newer aircraft sporting larger bypass ratio engines phase out older aircraft that hush kits benefited the most. In addition, hush kits cannot be used with other nozzle modifications. Thus, chevrons will almost always be the superior technology to use in place of hush kits, as the former does not carry nearly as much of a performance, mass, and aerodynamic penalty. For now, hush kits may still be a viable companion of older aircraft, but they are very much left in the sunset of aircraft noise reduction technologies.

Finally, mixer and scarfed fan nozzles scored at the bottom, with the former having a score of 0.2 and the latter being disqualified entirely. Mixer nozzles' weak noise reduction capabilities, relatively high thrust penalty, and moderate practicality place them firmly behind chevrons and hush kits. Meanwhile, scarfed fan nozzles were the only method studied that increased jet noise. As a result, both of these technologies are unlikely to hold the future of quieter aviation. As time progresses, it is very likely that these rankings will change. Notably, technologies considered too complicated today may appear less so as airliners continue to replace their older aircraft with newer ones. Airliners would not have to worry about potential engine internal redesigns either if they were in a position to acquire new jets anyway. These series of changes would benefit technologies like microjet injection the most. After all, it will only incur a performance penalty when active. Aircraft would be able to achieve lower noises near the ground and negligible losses in efficiency at cruising altitude.

Additionally, the commercial aviation industry continues to head toward larger and larger bypass ratio engines. Thus, aircraft engine noise will depend more on fan noise in the future. These circumstances may incentivize the application of serrations, among other techniques discussed thus far, along the engine inlet rather than at the exhaust. The engine fans' proximity to incoming air may also open up additional opportunities to better shape airflow, giving birth to entirely new suites of techniques previously incompatible with the exhaust jet. As more research and development efforts pool in, fan noise reduction technologies may come to rival traditional jet noise reduction strategies in the future.

Limitations

This review consisted of potential limitations that may have affected the final evaluation of the decision matrix, particularly around inevitable discrepancies in testing methodologies within the data gathered and the rubric of the decision matrix itself.

While measures discussed in Section 3 ensure the data used in the decision matrix have a certain level of consistency, some variables were not strictly controlled. Most notably, the conditions of the testing facilities were not fully standardized between different studies. This allows for comparisons between different sources, but minute differences in microphone placement, for instance, would have affected sound pressure level recordings. However, since improvements brought by noise control methods were calculated by the difference in noise output between a baseline nozzle tested under identical conditions for all articles presented in this paper, the effect would have been fairly minimal. Additionally, technologies yet to be tested with a jet performing fly-bys had to use OASPL metrics instead of EPNL, making them less representative of how an actual aircraft using these noise reduction methods may sound. Until these fledgling technologies tested with OASPL receive further development, however, EPNL measurements would remain impossible, making OASPL the second-most ideal by default.

The decision matrix also has an inevitable amount of subjectivity that must be addressed. Most notably, the weaker weight on the practicality score slightly favors more rewarding but more difficult-to-implement methods. Thus, these scores should not be interpreted beyond the scope of a mixed consideration between the current and near-future applicability of aircraft noise reduction methods. Furthermore, the balance between noise reduction and performance penalties in the decision matrix is such that an additional decibel of noise reduction is considered worth another 1% decrease in thrust. In reality, different aircraft manufacturers and airlines may strike a different balance between maximizing noise reduction or minimizing the loss in thrust. A notable omission in all measures discussed is the cost component of the noise reduction methods.

Unfortunately, this metric heavily depends on the manufacturing processes, production scale, material costs, and other aspects, such as the funds needed for research and development. These considerations usually vary wildly depending on the manufacturer and are not publicly accessible. As a matter of fact, none of the papers studied in this review discussed the aforementioned metrics. To address this shortcoming, the decision matrix used the practicality category to approximate the aforementioned sources of expense and take them into consideration. For instance, technologies that increase engine mass were penalized in the practicality score as they would cause additional stress to the airframe and necessitate more frequent maintenance. Active noise control methods were penalized even further, as they would require thorough inspections of highly sensitive and sophisticated sensor arrays essential to the technology's operation. However, such measures are inherently imperfect and can only approximate a limited range of cost considerations.

Conclusions

All in all, the usage of chevrons and other types of serrated nozzles remains the best jet noise reduction technology today, and indeed, they are being incorporated into modern 21st-century jet airliners¹² at this point. However, microjet injection technologies may be a worthy companion of chevrons in the future, providing cumulative noise reduction benefits without contributing to additional performance losses.

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References

- 1 M. Basner, C. Clark, A. Hansell, J. I. Hileman, S. Janssen, K. Shepherd and V. Sparrow, *Noise Health*, 2017, **19**, 41–50.
- 2 W. Babisch, *Noise Health*, 2002, **4**, 1–11.
- 3 E. van Kempen, I. van Kamp, P. Fischer, H. Davies, D. Houthuijs, R. Stellato, C. Clark and S. Stanfeld, *Occupational and Environmental Medicine*, 2006, **63**, 632–639.
- 4 D. Huang, X. Song, Q. Cui, J. Tian, Q. Wang and K. Yang, *Noise Health*, 2015, **17**, 93–97.
- 5 W. Babisch and I. van Kamp, *Noise Health*, 2009, **11**, 161–168.
- 6 S. Hygge, G. W. Evans and M. Bullinger, *Psychological Science*, 2002, **13**, 469–473.

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- 7 C. Clark, R. Martin, E. van Kempen, A. T. Head and J. Davies, *American Journal of Epidemiology*, 2006, **163**, 27–37.
 - 8 S. A. Stansfeld, B. Berglund, C. Clark, I. Lopez-Barrío, P. Fischer, E. Ohrström, M. M. Haines, J. Head, S. Hygge, I. van Kamp, B. F. Berry and R. study team, *The Lancet*, 2005, **365**, 1942–1949.
 - 9 T. Raef, A. Elzahaby and M. Khalil, *Jet Noise Reduction with Micro Turbojet Engine Noise Investigations*, 2015.
 - 10 L. Leyeikian, M. Lebrun and P. Lempereur, *AerospaceLab Journal*, 2014, **7**, 1–15.
 - 11 M. Azimi and F. Ommi, *Journal of Mechanical Engineering and Technology*, 2013, **16**, 25–32.
 - 12 S. Martens, *Jet noise reduction technology development at GE aircraft engines*, 2002, Retrieved from <https://api.semanticscholar.org/CorpusID:4988863>.
 - 13 M. K. Khalil, T. Raef and A. A. Elzahaby, *The International Conference on Applied Mechanics and Mechanical Engineering*, 2014, pp. 1–24.
 - 14 D. Bartlett, *Journal of Applied Science and Arts*, 2016, **1**, 1–11.
 - 15 J. K. C. Low, P. S. Schweiger, J. W. Premo, T. Barber and N. H. Saiyed, *Advanced subsonic technology (AST) separate-flow high-bypass ratio nozzle noise reduction program test report*, 2000, Retrieved from <https://api.semanticscholar.org/CorpusID:107152477>.
 - 16 N. Saiyed, J. Bridges and K. Mikkelsen, *Acoustic and thrust separate-flow exhaust nozzle with mixing devices for high-bypass-ratio engines*, 2000, Retrieved from <https://doi.org/10.2514/6.2000-1961>.
 - 17 V. G. Mengle, W. N. Dalton, J. C. Bridges and K. C. Boyd, *Noise reduction with lobed mixers: nozzle-length and free-jet speed effects*, 1997, Retrieved from <https://doi.org/10.2514/6.1997-1682>.
 - 18 *Help Me Decide*, 2000, Retrieved from <https://saeninfo.files.wordpress.com/2013/04/hushkits-2.pdf>.
 - 19 G. Gilbert, *Quiet Technologies gets STC for GIII/III hush kit*, 2007, Retrieved from <https://www.ainonline.com/aviation-news/2007-10-12/quiet-technologies-gets-tc-giiiii-hush-kit>.
 - 20 *Stage 3 kit configurations*, 2000, Retrieved from <http://www.fedex.com/us/hustkit/configuration>.
 - 21 W. D. Solomon Jr., K. W. Kinzie and D. B. Schein, *AIAA Journal*, 2002, **7**, 1–11.
 - 22 A. van Beem, *Rolls Royce Conway Mk508 (1959) used in Boeing 707-420 at Flugausstellung Hermeskeil*, 2014, Retrieved from [https://commons.wikimedia.org/wiki/File:Rolls_Royce_Conway_Mk508_\(1959\)_used_in_Boeing_707-420_at_Flugausstellung_Hermeskeil,_pic1.JPG](https://commons.wikimedia.org/wiki/File:Rolls_Royce_Conway_Mk508_(1959)_used_in_Boeing_707-420_at_Flugausstellung_Hermeskeil,_pic1.JPG).
 - 23 K. K. Ahuja, R. J. Gaeta, B. M. Hellman, D. B. Schein, W. D. Solomon Jr. and D. L. Huff, *Distributed exhaust nozzles for jet noise reduction*, 2001, Retrieved from <https://api.semanticscholar.org/CorpusID:118270925>.
 - 24 S. Harrison, E. Gutmark and S. Martens, *Jet Noise Reduction by Fluidic Injection on a Separate Flow Exhaust System*, 2007.
 - 25 B. S. Henderson and K. W. Kinzie, *Impact of fluidic chevrons on jet noise*, 2005, Retrieved from <https://ntrs.nasa.gov/api/citations/20050215037/downloads/20050215037.pdf>.