Aircraft Noise Reduction Technologies

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In this report, we survey the field of aircraft noise reduction. We first define why this is a key public health issue, before looking at the key causes, current noise reduction technologies, and finally what technologies and techniques we expect to see adopted in the future. We conclude with a look forward at how aircraft manufactures intend to use emerging tech to meet increasingly stringent international aircraft noise regulations while meeting sometimes conflicting goals for increased efficiency.

I. Nomenclature

ANC	=	Active Noise Cancellation
BLI	=	Boundary Layer Ingestion
BPR	=	Bypass Ratio
CAA	=	Computational Aeroacoustics
$EPNdB$	=	Effective perceived noise in decibels
FAA	=	Federal Aviation Administration
LES	=	Large-Eddy Simulation
$RANS$	=	Reynolds Averaged Navier Stokes

II. Background

In recent years, the primary focus of commercial aircraft engineers has been on making aircraft more efficient. Gains in efficiency lead to lower operational costs, making their product more attractive to customers, namely airlines. While this leading objective has paved the way for innovation in engine design and aerodynamics, another important factor has crept into the minds of aircraft engineers. This is noise pollution. Increasingly stringent noise regulations from air traffic regulators like the United States' Federal Aviation Administration (FAA), The International Civil Aviation Organization (ICAO) and others have sought to limit the harmful affects of aircraft noise on both passengers and surrounding communities [1].

A. Noise Regulation

In the United States, aircraft noise emissions come under the purvue of the FAA and their noise "Stages". In 1969, we first saw noise regulations for transport category jet aircraft operating in the US. These larger aircraft were subject to "Effective Perceived Noise Level" (EPNdb) [2]. This is not just a raw measurement of decibels (dB), but scaled based on the frequency range, with high frequencies being perceived as louder to humans. It is important to note here that the dB scale is logarithmic, meaning a 10dB drop is equivalent to half the noise. These regulations enforced different noise thresholds for takeoff and approach locations as the aircraft moved by monitoring equipment around the greater airport area. In 1974 this expanded to include propeller aircraft before 1977 with the introduction of the now codified "Stages" system. The Stages established in 1977 were Stage 1, Stage 2, and Stage 3. Stage 2, refers to aircraft meeting the early 1969 standards. Stage 3 refer to aircraft meeting the more stringent 1977 noise standards. Stage 1 refers to aircraft that do not fit into any of the standards laid out so far [2].

In 2005 we saw the adoption of Stage 4 noise regulation in the US. These limits were a full 10dB less than the previous Stage 3 standard and would apply to new aircraft being certified after January 1st, 2006. It however does not stop the production of aircraft already in production that do not meet this standard by 2006 (although it is reported that almost all aircraft manufactured in recent years before this regulation already met the Stage 4 standards). Most recently the 2018 adoption of State 5 standards for jets and large turboprop aircraft further reduces the noise requirement by about 7dB [1]. In December of this year (2020), Stage 5 noise restriction go into affect for small aircraft as well. Figure 1 shows the EPNdB of various aircraft on departure and arrival over the years compared with the noise stages defined by the FAA. Of note is the higher noise levels on departure compared to approach. As we expect to see ICAO and FAA work in tandem to institute more restrictive noise regulations, aircraft makers and aircraft operators must work together to see this noise reduction through to reality.

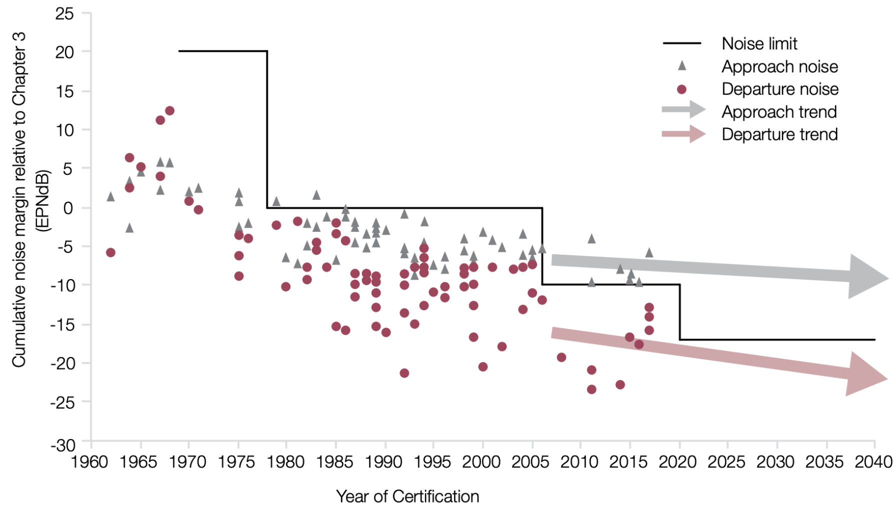

Fig. 1 Plot of Aircraft Noise vs Noise Margin compared to FAA "Stage 3" regulations [3]

B. Noise Health Effects

Why is noise reduction such a huge issue for regulators? FAA administrator Michael Huerta said this during the rollout of Stage 5 regulations. "Reducing aircraft noise is important to the FAA because it's an important quality of life issue for surrounding airport communities" [4]. A study from the Noise and Health Journal said this about aircraft noise pollution: "It can cause community annoyance, disrupt sleep, adversely affect academic performance of children, and could increase the risk for cardiovascular disease of people living in the vicinity of airports" [5]. The affects of aircraft noise are not limited to the annoyingly loud hum of the aircraft engines for the passengers on board, but extend deeply into communities living near to airports. In some cases, these communities live in these areas because of outside societal factors which prohibit them from moving elsewhere. It is an important issue of public health equity and should be taken very seriously.

While the majority of Americans do not live directly under the flight path of a large international airport, the issue of aircraft noise is something that you cannot ignore when onboard a flight. Passenger comfort can be greatly improved by lowering noise levels. You will arrive at your destination fresher and with more energy [6]. Improving the cabin comfort is perhaps a secondary goal to reducing external aircraft noise but can be an important factor for airlines.

C. Outline of Our Approach

As aircraft manufacturers seek to comply with these increasingly strict noise regulations, we will first look at what aspects of the aircraft produce noise emissions. After this, we will look at a range of mitigation technologies currently being explored. Then we will look at the current research allowing us to model the acoustic signature of aircraft which allows aircraft engineers to better design quiet aircraft. We'll conclude with what this means for future aircraft designs.

III. Key Noise Sources

A. Propulsion Noise

The headlining source of aircraft noise is propulsion noise. Everyone who's been on an aircraft can recall the sometimes deafening roar of the engines as the pilot applies takeoff thrust. It's important for this investigation that we understand the key sources of noise inside a jet engine. This will guide our investigation on how engineers are reducing noise. While specific to jet engines, may of the issues outlines here can be extended to propeller and even electric propulsion systems. We will start at the front of the jet engine and move rearward.

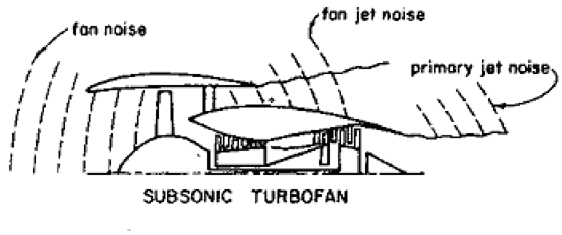

Fig. 2 Engine Noise Diagram [7]

1. Fan Section

The fan section of a modern jet engines provides the majority of the thrust. This is the result of newer subsonically operating engines having a high bypass ratio (BPR) design. BPR refers to the percentage of air bypassing the core and being only acted on by the front fan. As aircraft manufactures spin this section faster and faster they have to be careful to not have the tip of the fan section break the sound barrier. This is especially possible if the fan diameter is large as $V_{tip} = \omega R$ where ω is the rotational speed of the engine and R is the radius of a fan blade. When the tips of the blades reach supersonic speeds, the shock wave they generate can be heard audibly as a sort of "Buzzsaw" type sound [8]. This noise which falls in the higher frequency range is particularly annoying to both passengers on the aircraft and those people in the flight path. As we noted in the definition of EPNdb, this frequency range should be quelled. As we transition to higher and higher bypass engines, and even un-ducted engines like turboprops and electric propulsion systems, keeping the tips of these propellers and fans subsonic and as slow as possible will be key to reducing the noise.

A number of engine manufactures are looking at short inlet designs. These promise increases in fuel efficiency on the order of 0.5-1% [9] [10]. The reduction in inlet length poses challenges to acoustics as this ducting shielded and directed the sound coming out of the fan section. This poses a new challenge for acoustics engineers moving forward. Currently the ducting at the front of the engine is used to condition the flow before it enters the fan section. This alleviates affects from crosswinds and helps either speed up or slow down the air depending on which flight regime we are in. Engine manufactures want to shorten this to reduce drag when cruising and the weight that this associated addition of material in front of the engine core adds.

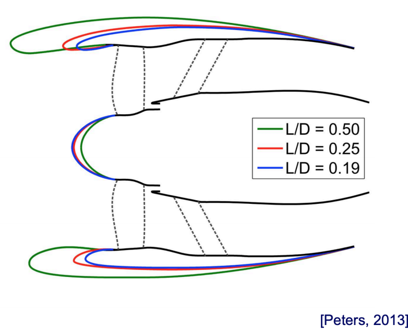

Fig. 3 Short Inlet Design, Length L vs. Diameter D[10]

2. Core and Reversers

Not to be ignored is the noise generated by the core. The core components are the compressor, combustor, and turbine. Key enhancements can be made to the rotor and stator designs inside the compressor and turbine to limit the amount of turbulence (and thus noise) that each stage generates. This has a key trade off in efficiency that must be balanced.

You will probably recall that during landing the engines of a modern airliner spin up to a higher power level. This occurs because the pilot deploys some sort of thrust reversing system. This typically diverts bypass air forward which helps slow the aircraft down on the ground. The nature of these designs often mean that they are redirecting high speed flow greater than 90 degrees. This often causes extreme turbulence as air that is being sucked in to the engine is being mixed with bypass air being directed forward. In addition to this, the air is now interacting with different surfaces of the aircraft instead of just flowing out the back of the engine. This is a recipe for a lot of noise pollution. Particularly to observers and communities near the airport. As engineers better model interactions between exhaust and reverser flows, we can better mitigate these noises.

3. Exhaust

A large majority of the noise emitted from the jet engine comes from the exhaust. Treatment of this air is crucial to reducing noise. Effectively the noise coming from a jet engine exhaust comes from the mixing of the hot and fast gas with the relatively slow and cold ambient air. Modeling this interaction has proven difficult for aerodynamicists and acoustic engineers. This sheering and mixing that occurs causes immense turbulence which in turn leads to noise. For low bypass or just turbojet aircraft, their noise emissions were enormous because there was effectively very hot exhaust mixing with very slow moving air. As we moved to higher and very high bypass engines, we have the addition of the lower speed air coming from the fan section. This effectively places an intermediary flow between the very fast moving core air and the slow moving ambient air. This mixing reduces the velocity gradient between the flows, reduces turbulence, and therefore noise. An important note is that noise increases as eighth power of the velocity difference" [8]. Small changes to reduce exhaust velocity have huge effects.

In the mitigation section we will look at how aircraft and engine manufactures can more predictably mix the flows and slow down the flows while still generating the required thrust for the specific application. A key takeaway here is that the majority of the noise isn't coming from the combustion of fuel like it would be in a car. This is why a drone is loud even with electric motors. The noise is coming from the turbulence of the air as it gets accelerated and mixed with the surrounding low speed ambient air.

B. Aerodynamic & Airframe Noise

While less significant in magnitude, the airframe itself is a contributor to noise pollution. Think for example of approaching for landing and you hear the landing gear get extended. This is accompanied by a noticeable increase in sound. This sound is the result of turbulence generated from the landing gear as it moves through the air. This is referred to as bluff body drag as the undercarriage of an aircraft is rarely considered for aerodynamics as its drag only occurs during a very short duration of the flight regime [8]. This regime, however is close to the ground and can be heard by ground observers.

"These noises are due to complex phenomena of boundary layer separation, laminar-to-turbulent boundary layer transition, shear layer transition, laminar separation bubble and associated dynamic effects" [11]. In addition to these expected noise sources, difficult to model resonances from open cavities also contribute greatly to the noise generated by landing gear. This remains a huge source of noise for aircraft like the Airbus A380 with a large undercarriage with many wheels and the related mechanisms allowing it to operate. [7]

Aerodynamic noise becomes increasingly prevalent with the usage of high lift devices. On many aircraft the flaps and slats increase the camber of the wing and can lead to an increase in turbulence on the trailing edge of the wing. As we've seen from the propulsion noise, the mixing of these two streams of air leads to turbulent air and noise. Another key cause are gaps in panels, for example gaps between the deployed high lift device and the rest of the wing. This can create local pressure gradients and so called "edge noise" which contributes significantly to aerodynamic noise [7]. Wing tip devices play a key role in reducing drag by stopping (or more predictably controlling) the mixing of the the lower and higher pressures air stream of the upper and lower surfaces of the wings. Again, better detection and modeling of these flows will allow acoustic engineers to remedy many of these issues.

C. Supersonics

While this could be an entire paper in and of itself, it is worth briefly mentioning supersonic aircraft and the issues presented by their operation. Due to the aerodynamic necessities of a supersonic wing, low speed flight is made more difficult. This mean higher approach and departure speeds compared to subsonic aircraft. To operate out of the same airports as subsonic aircraft, these aircraft must be have higher thrust rating at takeoff. In addition to this, supersonic

Fig. 4 Shielding on Landing Gear of Boeing 777 [12]

engine designs favor low bypass turbofans compared to high bypass turbofans of subsonic aircraft. As we've mentioned before, high speed hot exhaust gasses cause interacting with ambient air without the addition of significant lower speed bypass air yields high noise levels.

Fig. 5 Concorde Afterburner Takeoff [13]

The Concorde, one of the only commercial supersonic aircraft, was notable for its inability to takeoff without the use of its afterburners. This device reignites the exhaust gasses downstream of the turbine to produce more thrust. The downside of this tech is the enormous sound it produces. The already low bypass of the Concorde was made even louder with this addition. This did not go unnoticed by airports and the communities surrounding them. A New York Times article published in 1977 talked of noise concerns with Concorde as it conducted its demo flights around the United States [14]. This article makes reference to the EPNdb of Concorde and of course mentioned the notorious sonic boom. The EPA also investigated and monitored the Concorde's noise abatement procedures during departure on some of its early trips to the US [15]. Noise abatement procedures refer to how airport operations affect how aircraft operate. This includes when aircraft decide to reduce thrust on climb out. An article by Berton et al. examined the effects of different noise abatement procedures for supersonic business jets and found optimal strategies for reducing the noise footprint on departure by smartly throttling the engines [16]. We will delve into this in the mitigation section later on.

IV. Mitigation Technology

A. Engine Design

Most of the focus of aircraft manufactures and aircraft engine manufactures have revolved around increasing efficiency of their products. This makes sense as fuel cost is a key consideration of their customers and might make one aircraft more competitive than another. A consequence of this push for fuel efficiency has led to the prominence of high bypass turbofans for most jet airliners. High bypass refers to the fraction of the air flowing through the engine that bypasses the core and is simply sped up by the large fan in the front of the engine. This creates a large volume of relatively low speed air which mixes with the hot and fast air that is combusted through the core of the engine. The mixing of these gasses greatly reduces noise.

The Boeing 787 Dreamliner aircraft were some of the first aircraft to feature a unique nacelle design whose aim is to reduce noise of the exhaust gases. The shaped edges on the rear of the engine nacelle called chevrons serve to smooth the mixing, which reduces the turbulence that creates noise [12]. "They are actually creating another layer of fluid at a intermediate speed between the air passing the external part of the engine (fan secondary flow) and the external flow, so that the jump of properties is smaller, turbulence gets reduced and sound is quieter"[12]. In Figure 6, you can see the much more gradual rolloff between the jet flow and the low speed ambient flow (shown in blue) for the engine with chevrons. This design decision actually has the aerodynamic penalty of increased drag, but the significant acoustic benefit which reduces the need for sound insulation in the fuselage of aircraft. This reduction in weight if very beneficial and offsets the loss in efficiency. The chevron count controls the spacing between the axial vortices, the chevron penetration into the exhaust stream controls the strength of the axial vortices, and the chevron length controls the distribution of vortices within axial vortices [12]. A high chevron count resulted in good low frequency reductions without considerable high-frequency penalty [8]. This contributes to a significantly quieter operation of the Dreamliner compared to other similarly sized jets.

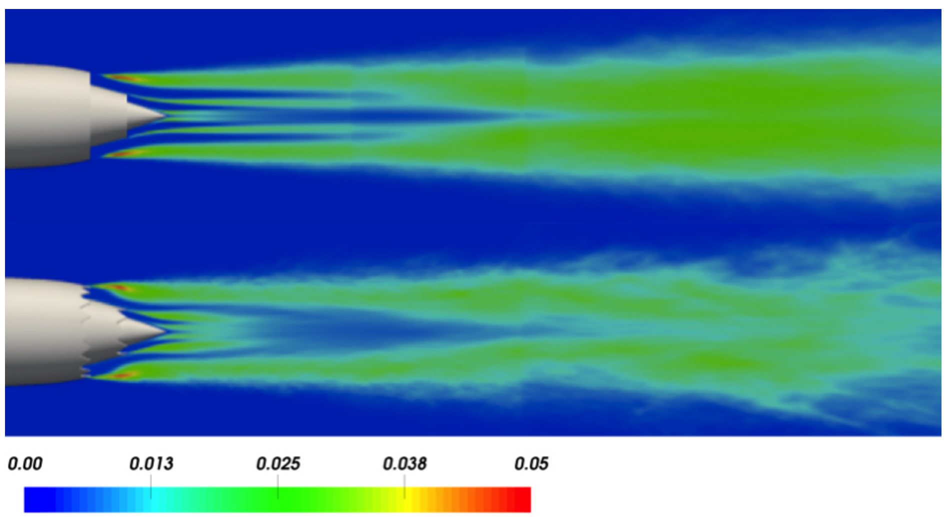

Fig. 6 Flow Simulation of Jet Exhaust with and without Chevrons [17]

The obvious next complication would be active chevrons which deploy into the exhaust at low altitudes and become flush at high altitudes when noise does not propagate to the ground with any considerable intensity. Burnett of Boeing said in 2005 that "[...] variable-geometry chevrons made with a temperature-reactive alloy [...] automatically warp into the jet exhaust flow to reduce noise during takeoff and landing and revert to a streamlined position at cruise altitude" [18]. Obviously more work is needed to ensure reliability and lightness of the components, but research continues to advance in this decade.

Another approach has focused on the inlet nacelle particularly the fan section. In particular keeping the fan tip speed subsonic. With high power settings, its is common for tip speeds to break the sound barrier. As we noted earlier, this results in loud shrieks and the "Buzzsaw" sound. The difficulty in reducing the fan speed as the fan gets larger and larger lies in ensuring the compressor stages still operate at their optimal design points and pressure ratios. The current solution involves adding in a gear box. Allowing the fan to operate at a slower rotational speed than the rest of the engine. This is a key design feature of the Pratt and Whitney PW1000G engine used on some Airbus A320neo aircraft. This engine and other recent engines utilize complex fan blade geometries to optimize for fuel efficiency and noise. New manufacturing techniques and materials makes this all possible [11].

Engine manufactures are increasingly interested in shorter inlet designs [19]. The advantage being less drag and better air ingenstion characteristics for differing angles of attack. The disadvantage being less shielding of the fan from the outside environment. Designers will have to weigh the 0.5-1% potential efficiency gains with the difficulty it will pose for noise control if we stick with conventional under wing engine configurations for the near future [20].

Several researchers have studied adding in active noise cancellation (ANC) to the front of the engine. Often the approach is flush-mounted loudspeakers inside the front section of the nacelle. "Unfortunately, because of weight, applications to turbofans are not straightforward, complexity of such devices and aerodynamic penalties" [18]. The signal processing and power required to do this on an industrial scale have prevented this from taking off.

The most low impact change engine designers can and have been making revolve around new materials developed by material scientist to deaden the sound emissions before they even leave the engine. "Boeing and Goodrich developed a one-piece acoustic barrel to line the inside of the engine nacelle inlet and also redesigned the inlet lip to enable sound-absorption without compromising deicing effectiveness. The barrel liner and the lip liner make almost the entire inner wall of the nacelle inlet sound absorbent" [18]. Advances in material science will be key to dampening the sounds coming from the core and fan sections.

B. Operational Changes

This entails changing how we control air traffic near the ground. A key aspect is low flying large aircraft which require aerodynamic devices like flaps to allow them to fly slowly. The combination of low flying and slow flying often requires high power output from the engines. If we can alter how aircraft descend into airports making this descent continuous and with the engines of the aircraft at low power settings, we can greatly reduce the amount of noise produced. Current FAA regulations dictate the glide path into most airports, increasing the steepness of this descent is desirable, but potentially difficult for pilots and current aircraft due to the lack of quiet drag devices [3]. Several researchers have looked at introducing swirling exhausts which increase the drag and decrease the effective idle thrust of the engines to allow for steeper approaches without adding noise from drag providing spoilers and other parasitic drag devices.

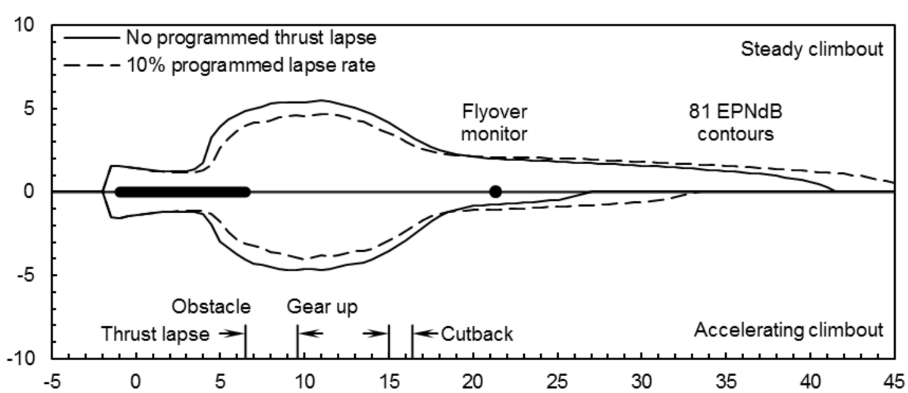

Fig. 7 Thrust Lapse Noise Signature [16]

A similar benefit can be realized with aircraft departures. There is a key trade off between climbing the aircraft quickly away from populated areas and the fact that doing so requires higher power setting and more noise. Finding the optimal climb path irrespective of ATC restrictions is something that Professor Kroo and others have looked at [21][22]. In a similar vein, [16] outlines a so called "thrust lapse" design. This takes advantage of "ground plane attenuation" which limits the lateral spread of noise due to ground affects. You can effectively make more noise closer to the ground and it will not propagate nearly as far. This affect diminishes in strength as the aircraft climbs away from the ground. It would be beneficial to automatically and gradually reduce power of the aircraft before the already common climb power phase of a takeoff. "Two advanced procedures – accelerating climb out and programmed thrust lapse – and their apparent necessity for supersonic transports are evaluated in this study by Berton et al. [16]. Results show these procedures are helpful in reducing lateral noise but may require departures from normal reference procedures defined by regulations. An accelerating climb out is shown to reduce both lateral and flyover noise, but a programmed thrust lapse is shown to reduce lateral noise at the expense of flyover noise" [16]. Applying this technique to subsonic aircraft would yield similar benefits, if safety and operational concerns could be alleviated.

C. Airframe Configurations

Most of the assumptions we've built about how aircraft noise propagates and is generated revolve around a standard aircraft configuration of a fuselage with underwing mounted engines. These are not the only aircraft configuration both in production and in the works. Many institutions and companies have demoed concept blended wing aircraft. This concept integrates the fuselage with the wings allowing the fuselage to generate lift. The overall design has considerably less drag than an underwing engined airliner. Figure 11 shows the efficiency gains we could expect with a blended wing aircraft. We've yet to see full scale demonstrator aircraft.

The Cambridge-MIT Silent Aircraft Initiative looks at potential tweaks to aircraft design and operation and design to allow for a virtually silent operation of aircraft outside of airport perimeters. This starts with increasing how steeply aircraft climb and descend into and out of airports like what Kroo and others have proposed. Of interest in this section is how the aircraft is designed. A blended body aircraft design with engines mounted above the fuselage. Above and beyond the lower drag and less induced noise from the fuselage, the mounting of the engines either above the aircraft or integrated into the body shields this large noise source from the ground. In practice ducted ultra high bypass turbofans with low specific thrusts are used to further decrease noise [3]. This design promises between a 20 and 25 dB decrease in noise from this shielding, 7 dB more than conventional airframe (with engines above wing) [3]. This design also takes advantage of boundary layer ingestion (BLI). BLI means that the engines ingest slower moving air than they otherwise would, increasing efficiency and allowing them to operate at lower power levels (less noise) [23]. This opens up the opportunity for geared turbofan with multiple fans in an array. This is not without new challenges. Namely having to deal with acoustic resonances of the swirl generated in this ducting inlet. As we will look at in next section, researchers are looking at how to better model these effects to accurately predict what changes in the configuration can have on these unpredictable factors like swirl and resonance.

Fig. 8 Silent Aircraft Initiative SAX40 Aircraft [3]

These radical departures from current airframe configurations are always exciting, but simpler airframe configuration changes like shrouding the landing gear with aerodynamic fairing can greatly reduce parasitic drag and noise. Figure 4 shows this concept applied to the landing gear bogeys of a Boeing 777. This can be retrofitted to existing designs at a relatively low cost. It is estimated that changes to the undercarriage can reduce noise by 1-2 EPNdB for a typical commercial airliner [11]. Similarly, changes to high lift devices like flaps by optimizing gaps can reduce noise emissions by up to 2 EPNdB [11]. Continuing innovation in acoustic modeling will only make studies like those done with the OPENAIR initiative more fruitful and applicable to the current fleet of aircraft in the skies.

V. Current Research Areas

The old adage "you cant manage what you cant measure" is very salient in the field of aeroacoustics. Over the years, we've improved our ability to capture real world data about aircraft noise. Technologies like acoustic holography allow us to target and the hopefully address of key noise sources. This however is very slow and does not help designers and engineers iterate to create optimal designs for both efficiency and low noise. Being able to compute the acoustic response both in the near field (near the aircraft) and far field (the surrounding communities) requires immense modeling complexity and fidelity. As we will see, a high degree of precision is needed to capture the intricacies of, say, the acoustic picture out of an engine nozzle. Propagating that far field though an unsteady atmosphere and being able to predict how that affects someone 10 miles from the airport is very difficult. The techniques we'll touch on in this section seek to make these computation more feasible and more beneficial outside of the academic world for industry experts to use. This will be especially important as we look towards the blended wing designs with complicated inlet ducting arrangements.

A. Modeling Aeroacoustics

Acoustic Holography refers to using an array of microphones to estimate the near field acoustics emissions of a particular location [24]. "Sonar, [] has its difficulties. It is great for identifying the presence and location of an object, but not very adept at identifying the features and identity of the object. In the far field reflection of the sound wave off of the object, many details of the wave are obscured or lost so it is very difficult to reconstruct an image from the information that is present. This is one reason why acoustic holography was developed around the 1960's"[25].

In Acoustic Holography, sound reflections off an object incident on a detector surface are compared with a reference wave, leading to a destructive and constructive interference pattern based on the surface details of the object [25]. The more recent field called near-field acoustic holography (NAH) improves on these techniques, but still faces difficulties in certain situations. Figure 9 shows an example of this applied to a car door. The scale required to model, say an engine exhaust is currently very expensive. Researches continue to find improvements in resolution, versatility, and functionality with NAH [25]. In general this technology is useful for detecting noise sources experimentally, but of no use for modeling and iterating on designs experimentally.

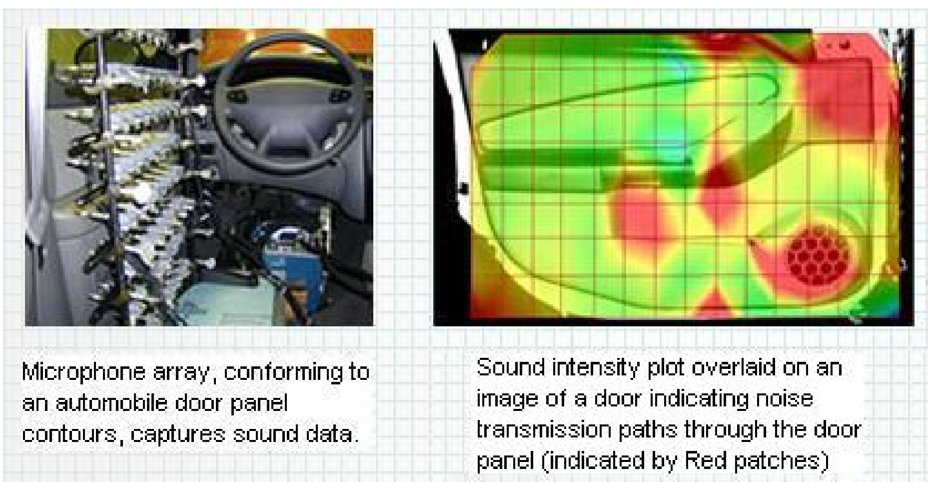

Fig. 9 Example of Acoustic Holography applied to car door

B. Acoustic Boundary Control

This method of noise reduction is primarily targeted at the interior of jet aircraft. It works by placing a distributed array of secondary acoustic sources inside the fuselage of the aircraft. Ideally constructed out of some smart material that could vibrate to generate the necessary acoustic signature to cancel the incoming sound from engines and other noise sources on the aircraft. This would then greatly reduce the acoustics entering the cabin. This has been investigated by Sun and Hirsch at the University of Delaware since the late 90s [26]. Its relative complexity and expense have meant this, like ANC, is still in the realm of research and has not yet seen adoption in industry. It has potential to be more effective than noise cancelling, but does nothing to quell external noise emissions.

C. Computational Aeroacoustics

The field of computational aeroacoustics is concerned with using numerical methods to analyze and predict noise from turbulent flows. The recent availability of high-fidelity simulation offers engineers the possibility to improve and calibrate empirical methods so that a "physics-based" method can be developed in the future [27]. This field came about in the late 80s and came into its own in the 90s with new computational technologies. A key example of CAA is the development of far field integration methods. This allows for solving the compressible Navier Stokes equations and obstaining useful results for aircraft noise far from the source. It is particularly more difficult than regular flows because it requires a higher level of resolution "due to the large differences in the length scale present between the acoustic variables and the flow variables [28]. Solving these equations often requires integral methods. Examples of these include the Lighthill's Method, Kirchhoff integral, and FW-H. These are beyond the scope of this paper but all come with associated tradeoffs and limitations for different flow regimes. Reynolds number and Mach number often cap the usefulness of these methods.

Professor Sanjiva Lele at Stanford has been investigating how we model noise in the form of aeroacoustic analysis [28] [29]. His tools have been very helpful for our understanding of aircraft noise pollution and things like wind turbine noise [30]. The difficulty in capturing the turbulent boundary layer accurately is the largest target of current research into Large-Eddy Simulations (LES) by Lele and others. As we've mentioned previously, this extremely thin boundary layer formed as the hot and fast exhaust gasses interact with the environment cause the bulk of the jet engine noise. Lele et al. point out that around 2008, the Reynolds Averaged Navier Stokes (RANS) methods became more applicable in its usage for modeling of the turbulence effects of engine exhausts. RANS previously was used to study noise propagation but only examined flow fields outside of nozzles [31]. This was then left to experimentalists to try to match the conditions to an actual nozzle by tuning many seemingly arbitrary parameters [29]. This proved difficult and at times intractable and "it was not possible to systematically study the effect of jet Mach number, jet temperature or jet nozzle design modification, e.g. chevrons or tabs, etc"[29]. Since the state of the gas at nozzle exit is the most critical factor for noise pollution, having models that accurately predict the boundary layer interaction and at realistic Reynolds numbers is critical [29].

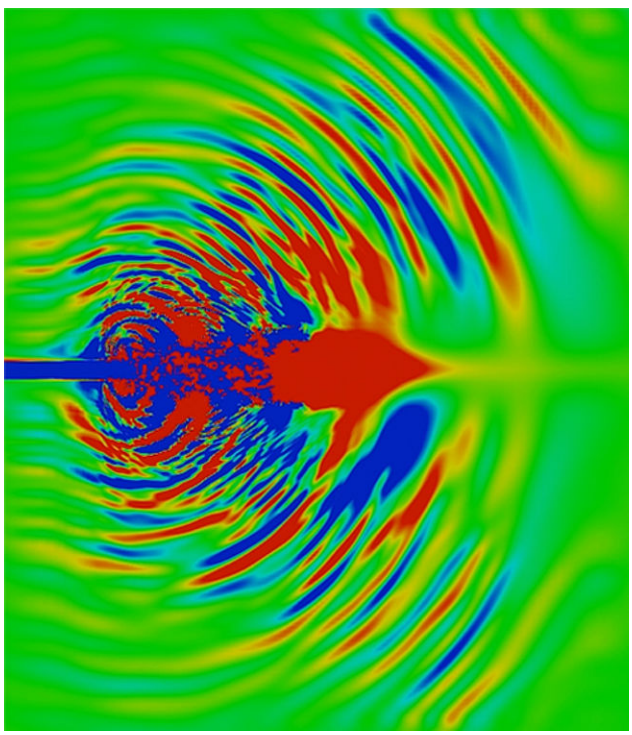

Fig. 10 Example sound field generated by jet engine [17]

In current techniques, the micro scale of turbulence within the noise-producing region of the jet are resolved with a high level of accuracy using CFD with RANS techniques. The results of this are then propagated from the near-field source region to the far field with analytical computation and some of the intergal methods I touched on earlier [28]. The Ffowcs Williams–Hawkings (FW–H) equation is one of the most commonly used hybrid methods [29]. It is one of the more tractable methods to gain insights far from the source region of noise. As computers continue to be able to numerically solve these exceedingly detailed and complex model faster, acoustics engineers and aircraft engineers can realize which small changes to things like aircraft configurations, engine geometries, and inlet designs both achieve the desired noise reductions and while maintaining stellar efficiency goals.

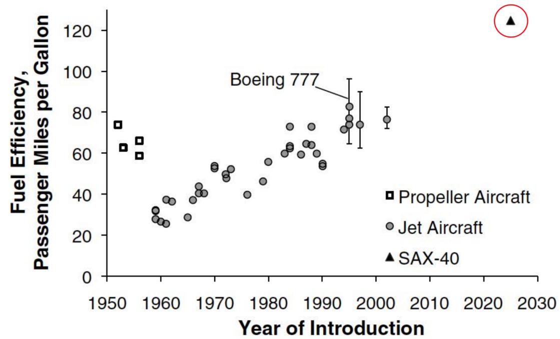

Fig. 11 Fuel Efficiency of SAX40 Compared to Existing Aircraft

VI. Conclusion

In this paper, we investigated the root causes of aircraft noise pollution. We found the reasons why this is such an important topic. The main issue being the long term health effects on communities near airports. With the recovery of aviation after COVID-19 and increasing frequency of air travel in the next decade plus, we should be deeply be concerned about this. We then looked at what technologies are currently being used to mitigate this nuisance. Finally we tackled the current and emerging research areas in both academia and in industry to look to what potential methods could be best utilized for aircraft noise suppression. All of these, together with strong international pressure from regulators indicate that there is a bright and quiet future for commercial aviation. There is no simple single solution to aircraft noise. It takes collaboration among all of these different aspects of aviation, and ideally a clean slate design like the blended wing aircraft concepts to really move past the airliner configurations we see today and keep our skies clean and quiet. We hope that the economic interests of airlines and aircraft manufactures will align to push us towards these new and innovative designs in the near future.

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