Far Term Noise Reduction Roadmap for the Mid-Fuselage Nacelle Subsonic Transport

Yueping Guo*
NEAT Consulting, Seal Beach, CA 90740 USA

and

Russell H. Thomas†, Ian A. Clark‡ and Jason C. June‡
NASA Langley Research Center, Hampton, VA 23681 USA

A noise reduction technology roadmap study is presented to determine the feasibility for the Mid-Fuselage Nacelle (MFN) aircraft concept to achieve the noise goal set by NASA for the Far Term time frame, beyond 2035. The study starts with updating the noise prediction of the existing MFN configuration that had been modeled for the time frame between 2025 and 2035. The updated prediction for the Mid Term time frame is 34.3 dB cumulative effective perceived noise level (EPNL) below the Stage 4 regulation. A suite of technologies that are deemed feasible to mature for practical implementation in the Far Term and whose potentials for noise reduction have been illustrated is selected for analysis. For each technology, component noise reduction is modeled either by available experimental data or by physics-based modeling with aircraft system level methods. The noise reduction is then applied to the corresponding noise component predicted by advanced aircraft system noise prediction tools, and the total aircraft noise is predicted as the incoherent summation of the components. It is shown that the Far Term MFN aircraft has the potential to achieve a cumulative noise level of 40.2 EPNL dB below Stage 4. The key technologies to achieve this low aircraft noise level are assessed by the impact of each technology on the aircraft system noise. This roadmap shows the potential of this revolutionary, yet still tube-and-wing, MFN concept to reach the NASA Far Term noise goal.

I. Introduction

In order to establish the roadmap for achieving the NASA noise reduction goal for the Far Term time frame beyond 2035, a study has been presented in Ref. [1], where a set of noise reduction technologies is applied to the Hybrid Wing Body (HWB) aircraft. These noise reductions, together with the inherent noise shielding features of this configuration, have shown the feasibility of reducing the aircraft noise certification metric of Effective Perceived Noise Level (EPNL) to 50.9 dB below the cumulative certification regulation of Stage 4 defined in the Code of Federal Regulations Title 14, Part 36. The noise reduction technologies considered in that study are not all exclusive to the HWB configuration. It is therefore of interest to apply the technologies to another promising aircraft configuration such as the Mid-Fuselage Nacelle (MFN) aircraft, a concept under study in recent years as a potential future advanced aircraft configuration. Furthermore, the MFN aircraft has its own unique design and noise features, and thus, a different ranking order of the noise components than the HWB. This may affect the impact of individual noise reduction technologies, either favorably or unfavorably. The noise reduction

* NEAT Consulting, 3830 Daisy Circle, Seal Beach, CA 90740, AIAA Associate Fellow
† Senior Research Engineer, Aeroacoustics Branch, MS 461, AIAA Associate Fellow
‡ Research Engineer, Aeroacoustics Branch, MS 461, AIAA Member

potential and the noise levels of different aircraft configurations are also determined by technologies that are unique to the individual designs. This study is motivated by all these aspects, and the objective is to predict the system noise of the MFN aircraft including the most advanced, effective noise reduction technologies expected to be mature in the NASA Far Term time frame.

The MFN aircraft concept is a NASA designed advanced aircraft configuration that retains the advantages of the conventional tube-and-wing (T+W) layout and makes use of the benefits of fuselage-mounted engines [2]. The most significant acoustic benefits include the ultrahigh bypass ratio engines, the inlet fan noise shielding by the wings, and the reduced ground clearance requirement that provides the opportunity for a redesigned landing gear assembly for noise reduction [1], [3]. The MFN aircraft concept has been included and studied in the NASA portfolio of the Environmentally Responsible Aviation (ERA) Project. Its noise levels have been assessed [4], [5] with technologies in the NASA Mid Term time frame between 2025 and 2035 to be about 33.4 EPNL dB below the cumulative certification limit of Stage 4. This is the starting point for the Far Term roadmap study conducted here for the NASA Advanced Air Transport Technology (AATT) Project.

The technologies selected in this roadmap were not included in the previous Mid Term study in Ref. [4] either because of their low Technology Readiness Level (TRL) at that time, the limited time available for development to the Mid Term time frame, or because they were developed after the conclusion of that study. The selection of the noise reduction concepts is based on solid theoretical considerations and/or successful proof-of-concept experimental demonstrations on the component noise. However, the inclusion of a potential technology in the roadmap depends on its impact on the total noise at the aircraft system level.

The aircraft system noise levels will be assessed by a ground-up approach in which component noise levels are predicted by improved capabilities in the research version of the NASA Aircraft NOise Prediction Program (ANOPP-Research). In this process, the component source levels, the effects of propulsion airframe aeroacoustic (PAA) integration, and noise reduction technologies are quantified by a combination of advanced component source prediction, experimental data processing, and noise reduction modeling. This captures the dominant physics of the source mechanisms and noise suppression, including the parametric variations of main features with frequency and far field directivity angles. The development of these capabilities has been an ongoing effort to improve aircraft noise prediction at NASA.

At the conceptual level, there is no detailed design for the aircraft configuration and the noise reduction technologies; however, the selection of the noise reduction concepts will follow a few principled guidelines. The study is an exploratory, pathfinding study focused on the noise reduction potential of various technologies and design features applicable to the MFN aircraft configuration. These technologies and design features should not result in unfavorable changes to the aircraft design. This will need to be confirmed in future studies and multidisciplinary analysis as part of the maturing process for this aircraft concept and technologies.

II. Baseline Configuration

The MFN is one of the advanced configurations studied at NASA in recent years [2], distinguishing itself from the conventional (engine-under-wing) T+W configuration with a double deck fuselage and two Geared Turbo Fan (GTF-like) engines mounted from the fuselage. The engines are positioned at the mid-fuselage location so that the inlets are over the trailing edge of the main wing. The overall aircraft layout and design features are similar to an advanced configuration studied by Boeing [6], [7]. The MFN aircraft concept is illustrated in Fig. 1.

Fig. 1 Illustration of the NASA MFN aircraft concept.

The airframe technologies include a lightweight structure enabled by damage arresting composites, natural laminar flow wings enabled by a Krueger leading edge high lift system, and laminar flow nacelles. The engine technologies include low fan pressure ratio engines with short nacelles, swept and leaned fan exit stators, a highly loaded high-pressure compressor enabling higher overall pressure ratios, and a low emission combustor. The aircraft is designed for the Large Twin Aisle class of 301 passengers, and the overall specifications, together with some parameters relevant to noise prediction, are listed in Table 1. After several years of refining the modeling at the conceptual level, the resulting aircraft model together with the fuel burn and emissions assessments were presented in 2016 in Ref. [2], and the final noise assessment results in Ref. [4].

Table 1 Vehicle model for MFN aircraft.

Fuselage	Double Deck
Engine	GTF
Engine Mounting	Fuselage
Leading Edge Device	Krueger
Trailing Edge Device	Simple Flap
Main Gear Type	6 Wheels
Takeoff Gross Weight	544,748 lb
Operating Empty Weight	259,943 lb
Payload	118,100 lb
Total Fuel	162,795 lb
Wing Span	208 ft
Thrust Per Engine	65,500 lb
Fan Diameter	149 in
Fan Rotor/Vane Count	16/36
Inlet Liner Length/Fan Diameter	0.33
After Duct Liner Length/Duct Height	1.57
Lift/Drag Ratio (Sideline/Cutback/Approach)	13.9/13.5/8.9
Bypass Ratio (Sideline/Cutback/Approach)	23.3/25.4/31.9
Fan Pressure Ratio (Sideline/Cutback/Approach)	1.3/1.2/1.1

The aircraft model and assessment results from 2016 are the starting point for the study presented here with the designation C0. Thus, for the convenience of discussions in subsequent sections, the noise levels for this baseline configuration are summarized in Table 2 for the three individual certification conditions at approach, cutback and sideline, as well as the cumulative noise level. The regulatory noise limits under Stage 4 for this aircraft are also listed in the table for comparison. As can be seen from the table, the certification limit for the cumulative level is required to be 10 dB less than the sum of the three individual limits. The table shows that the cumulative EPNL margin of this aircraft is about 33.4 dB referenced to the regulation of Stage 4, defined in the Code of Federal Regulations Title 14, Part 36. The aircraft noise regulation currently in effect is Stage 5, or Chapter 14, which is more stringent than Stage 4 by 1 dB at each individual measurement condition and by 7 dB for the cumulative level. Because the NASA noise goals were established in reference to Stage 4 and are commonly referred to as such, this reference will be used in this paper. Based on the prior work, the MFN aircraft has the potential to meet the NASA Mid Term noise goal.

Table 2 MFN aircraft EPNL with Mid Term technology [4].

	Approach	*Cutback*	*Sideline*	*Cumulative*
MFN (C0)	91.0	84.8	85.0	260.8
Stage 4 Limit	104.6	98.4	101.2	294.2
Margin to Stage 3	13.6	13.6	16.2	43.4
Margin to Stage 4	-	-	-	33.4
NASA Mid Term Goal	-	-	-	32 - 42

There are a few technologies that have helped this Mid Term aircraft to achieve such low levels, which will be carried over to the Far Term aircraft and are quoted from [4] in Fig. 2. These include the combined impact of noise shielding and reflections due to propulsion airframe aeroacoustic (PAA) integration, soft vane and multidegree of freedom (MDOF) liners for fan noise reduction, partial fairings on the main landing gear (MG), and flap side edge treatment by porous material. The height of the color bars in this figure, denoted by ΔEPNL (dB), is the noise reduction in aircraft EPNL provided by each individual technology. As will be seen later in the paper, these values of noise reduction will change for the Far Term aircraft because of the application of additional noise reduction technologies that alter the ranking order of the noise components, and correspondingly, change the noise reduction efficiency of the individual technologies.

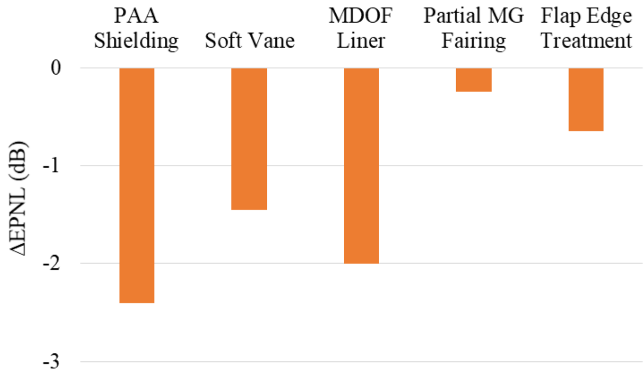

Fig. 2 Impact of individual technologies on Mid Term MFN aircraft [4].

The low noise levels of the MFN aircraft for the Mid Term configuration result from favorable configuration design, advanced engines, and a series of noise reduction technologies, as detailed in Refs. [2], [4]. For comparison, it can be noted that the most recent wide body aircraft entering into service, namely, the Airbus A350 and the Boeing 787, have average noise levels that are 20 dB below Stage 4 for the cumulative EPNL.

III. Prediction Methodology

The prediction methodology used in this study follows the system noise prediction process implemented in the research version of the NASA Aircraft NOise Prediction Program (ANOPP-Research), which is based on the predictions of individual noise components and the integration of the components into the total noise prediction on the basis of incoherent energy summation. The integration of individual noise components also accounts for the effects of PAA and individual noise reductions [8], [9]. This is the method used in many previous aircraft system noise studies [1], [3]-[5], [10], [11] involving both conventional and unconventional aircraft configurations. The high level methodology is illustrated in Fig. 3, which includes three main elements. The first is component source prediction. This element utilizes the best component noise prediction practices, databases, and methods developed at NASA and in the aerospace industry over the previous decades. The original, currently released version of ANOPP is mostly focused on conventional designs with prediction capabilities for the current generation of engines and aircraft. These capabilities have been expanded to better predict unconventional aircraft in ANOPP-Research. The second and the third elements in Fig. 3 are the modeling of noise reduction effects and the prediction of the PAA integration effects from acoustic scattering and flow interactions. These are implemented as a process based on experimental databases and/or physics-based modeling, enabling the effects to be modeled with variations with frequency and directivity angles.

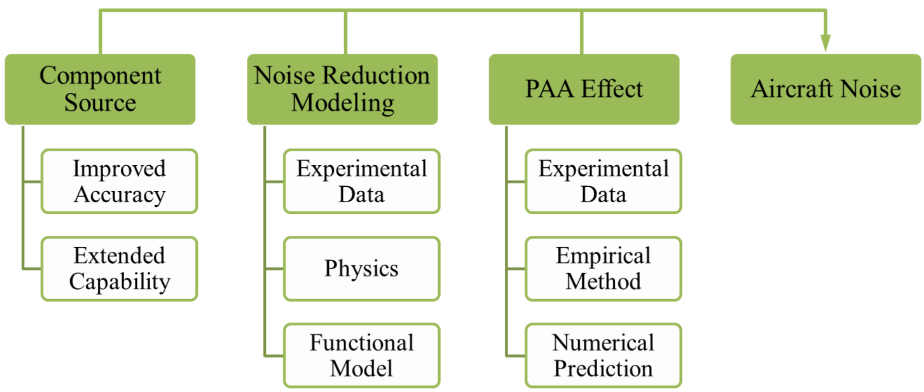

Fig. 3 Prediction methodology in ANOPP-Research.

As an ongoing effort, the capabilities in ANOPP-Research have been continuously expanded and improved for better accuracy and robustness, including the development of more accurate individual prediction models and the incorporation of the most relevant experimental data. Table 3 briefly summarizes some of the advanced features that enable system noise studies for advanced aircraft concepts, where the first column lists the elements of the advanced prediction capabilities and the second column explains the improvements and their respective effects on the component prediction. It is clear from the table that some of the enabling features are new additions to the prediction capability, while others are improvements and updates on previous methods and theories. The new features cover component noise source models, propagation effects, and noise reduction.

Table 3 Some of the Improvements in ANOPP-Research.

Element	***Improvement***
Landing Gear	▪ Reflection model with realistic source distribution ▪ Low velocity flow and sound absorption for noise reduction
Leading Edge Device	▪ Krueger noise prediction model ▪ Noise reduction treatment module: sealed gap, cove filler, bracket alignment, dual use fairing
Flap Side Edge	▪ Prediction capability for continuous flap system such as Boeing 787 ▪ Noise reduction module: porous surface, continuous mold line
PAA Effect	▪ Empirical prediction process based on mapping of test data ▪ Model to predict complete azimuthal and polar range of data
LINER Module	▪ Based on TREAT and includes the impact of MDOF liners ▪ Improved non-dimensional scaling ▪ Improved high frequency fall off for MDOF liners

While the detailed discussions of the prediction tool development are not the topic of this paper, it is appropriate to discuss the prediction capability and aircraft modeling improvements relevant to the MFN aircraft. A brief summary is given in Table 4 for the individual methods and design features that are different from those used in the baseline case discussed in the previous section and reported in Ref. [4]. For the convenience of discussion, a configuration number is assigned to each improvement, starting with C0 to represent the final result of Ref. [4].

Table 4 Improved methods and design features for MFN aircraft.

Configuration	*Description*	*Main Improvement*
C0	Baseline Configuration	-
C1	Gear Strut Length	Corrected to Exposed Length for Landing Gear Noise
C2	Acoustic Liner Design	Tuned Duct Liner to Dominant Frequency for Fan Noise Reduction
C3	Liner Correction	Corrected Inter-Stage Liner Effectiveness for Fan Noise Reduction
C4	Additional Liner	Added Bifurcation Liner for Aft Fan Noise Reduction
C5	Prediction Tool	• Improved Krueger Noise Model • Flap Side Edge Noise Model • Data Mapping Method for PAA • Gear Noise Reflection

As can be seen from the table, the improvements include more realistic modeling of the aircraft features, as well as improved prediction tools. These improvements are for the purpose of more accurate predictions and can lead to either higher or lower noise levels than before. The first correction is C1, concerning the use of main landing gear strut length in the noise prediction. In previous studies [4], [12], total strut length was used as an input to the landing gear noise prediction. This is incorrect because a portion of the strut is inside the landing gear cavity with a lower velocity, and therefore, lower noise generation. The more appropriate length of the gear strut to use is that exposed to the external flow. This was highlighted in the work reported in [13]. For the MFN aircraft, the main gear cavity depth and the nose gear cavity depth are estimated, which leads to exposed strut lengths that are 2.2 feet and 1.6 feet shorter than the total structural lengths for the main and the nose gear, respectively. This correction correspondingly lowered the noise for both the main and the nose landing gear even after accounting for the difference in gear noise reflection from the airframe.

The configurations C2 and C3 are both for corrections in the acoustic liner design. For the acoustic duct attenuation prediction, the TREAT method is used. This is implemented in ANOPP as a module to predict liner effects [8], [9] and modified in several ways including the incorporation of multidegree of freedom (MDOF) liner technology. In the ERA study summarized in the previous section, the liner was not tuned to the most effective frequencies, probably due to the lack of information on the engine noise. However, tuning the liner is a common practice in engine liner design, and therefore, it is a logical improvement to the prediction of the MFN aircraft. The liner prediction correction in C3 concerns the interstage liner treatment. NASA subject matter experts estimate that only 50% effectiveness should apply to the actual length of the interstage liner. Therefore, similar to Ref. [12], for the GTF-like engine used for the MFN aircraft, the effective length is now set at 0.28 of the duct height (50% of the actual length).

Another realistic liner treatment issue is the application of acoustic liner to the bifurcation of the aft fan duct, considered in C4. The TREAT method does not automatically include treatment on the bifurcation. In modern large engines, and likely in future engines, bifurcation treatment is common and, therefore, is logically applied here. For the MFN aircraft engine, the bifurcation is connected to the supporting strut that mounts the engine to the fuselage. Thus, the bifurcation on the inner side closer to the fuselage is thicker and the one on the outer side is thinner. Accordingly, treatment is applied to the inner, thicker bifurcation to cover 75% of the available area and to the outer, thinner bifurcation to cover 50% of the available area.

In addition to the design corrections and improvements discussed in the above paragraphs, another area of significant change is the improvement of the prediction tools. The improvements update the original version of the prediction tool [14] with more accurate modeling of the reflection of the bracket noise by the deployed Krueger itself. This change impacts the directivity of the bracket subcomponent of the Krueger noise, and thus, the Krueger noise component as a whole. The prediction of flap side edge noise is also improved by an updated version of the prediction tool from the original version reported in Ref. [15] that incorporates the advanced design approach of continuous trailing edge high lift elements. This has been the design philosophy in the Airbus family of aircraft and has been incorporated in the latest Boeing aircraft, the Boeing 787. These two improvements are applied at C5. Furthermore, the landing gear noise reflection model has been refined with more distributed sources. Source distribution for landing gear noise is not an issue for far field noise calculation because the propagation distance is much larger than the source separations so that there is little difference in the noise levels in the far field between a single-source model and a multi-source model, as long as the total source strength is the same for both cases. However, the source distribution can affect the noise reflected from the wing and the fuselage, because the propagation distances from the sources to the reflection points are comparable to, or even smaller than, the source separations. Yet another methodology improvement is the shielding prediction of fan inlet noise by the wing and the jet and aft fan noise by the fuselage, which is a prominent acoustic feature for the MFN aircraft. This feature has been accounted for by a method that maps wind tunnel test data at different configurations to the MFN geometry. The method is obviously empirical in nature and involves various assumptions.

With the above corrections and improvement, the configuration C5 represents a new Mid Term baseline before any Far Term noise reduction technology is applied. To illustrate the effects of these corrections and improvements in the predictions, Table 5 shows the changes from the baseline, C0, to the new baseline, C5. At first glance, the changes in the noise levels seem insignificant, less than 1 dB for all the cases. It becomes clear from the details of the improvements that the small changes in the total noise levels are due to two reasons. The first is that some improvements increase the noise, while others decrease the noise. The total noise levels include cancellations of the individual effects. These individual effects will play an important role in noise reduction because they affect the ranking order of the individual noise components. The second reason is that an individual improvement in the prediction usually only changes the level of one noise component, while the total noise is the summation of all components, weighting down the individual effect, especially if the affected component is not the highest noise component.

Table 5 Effects of prediction improvements on MFN aircraft EPNL (dB).

	Approach	*Cutback*	*Sideline*	*Cumulative*
Baseline from ERA (C0)	91.0	84.8	85.0	260.7
New Baseline (C5)	90.4	84.7	84.8	259.9
Noise Change	-0.6	0.0	-0.2	-0.8

The relative amplitudes of the noise components of the C5 configuration are given in Fig. 4 for the three certification conditions. Overall, the fan noise makes significant contributions at all three conditions, and the airframe noise components are major contributors to the approach noise, especially the main landing gear noise. It is then clear that a successful noise reduction strategy should be first focused on the fan and the main landing gear components. Overall noise reduction should also consider the reduction of other components because their levels are usually only a few decibels lower, and thus, can easily hold up the overall noise reduction once the major components are reduced.

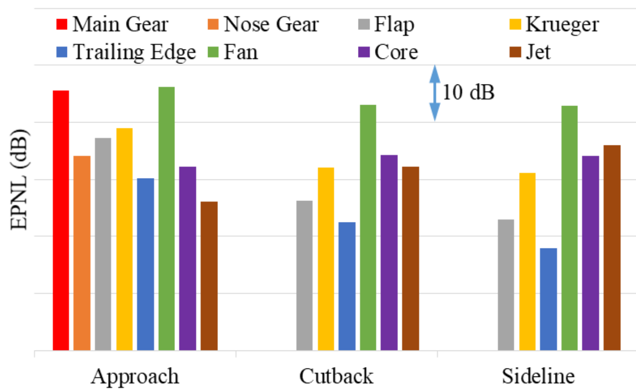

Fig. 4 Noise component of baseline (C5) MFN aircraft noise.

IV. Engine Noise Reduction

From the relative amplitudes shown in Fig. 4, it is clear that Far Term engine noise reduction should be primarily focused on fan noise. Four liner treatment technologies are selected, respectively designated as C7, C8, C9 and C11, and are summarized in Table 6 with brief descriptions. The technologies are also graphically illustrated in Fig. 5. The discontinuous numbering of the configurations is in order to be consistent with the HWB roadmap study reported in Ref. [1] so that the same technology in the two cases is denoted by the same configuration number. Since both the HWB and the MFN aircraft use similar GTF-like engines, there are many common technologies between the two for engine noise reduction.

Table 6 Engine noise reduction concepts for Far Term roadmap.

Configuration	*Technology*	*Target Noise*
C7	Inlet Lip Liner	Fan Inlet Noise
C8	Center Plug Liner	Engine Core Noise
C9	Over-the-Rotor Liner	Fan Noise
C11	Increased Bifurcation Liner	Aft Fan Noise

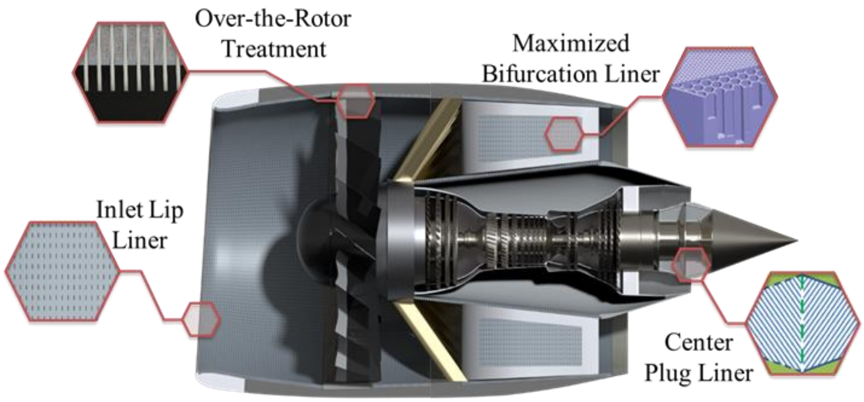

Fig. 5 Illustration of Far Term engine noise reduction technologies.

Acoustic lining for aircraft engine inlet noise reduction usually extends from the fan casing to the inlet throat. As engine nacelles are shortened to reduce weight and drag, the noise reduction from the inlet duct liner is correspondingly reduced due to the loss of treatment area. Extending the liner to the lip of the inlet has been an attractive option to compensate for the shortened nacelle length. The technology has been investigated in recent years, in the Quiet Technology Demonstrator 2 (QTD2) flight test led by Boeing with participation from NASA and other aerospace companies [13], [16]. It is recognized that for this technology to mature, challenges such icing protection, aerodynamic drag, and inlet off-design performance have to be overcome, which has led to continued research and development. It is reasonable to expect this technology to be ready for service well within the NASA Far Term time frame. To predict the impact of the inlet lip liner for the use in C7, the available TREAT method, including MDOF liner technology, is used by extending the liner treatment length out to the full inlet length available on the short inlet designed for the GTF-like engine on the MFN aircraft.

For low frequency combustor noise, there has been promising development of a folding cavity liner applied to the center plug; the concept was tested on a GE CF34 engine [17], [18]. The perforated face sheet of the liner covers the converging section of the core nozzle plug. For the current study of the MFN aircraft, a suppression map is developed based on the test results reported in the above references, with peak attenuation of just over 8 dB at 400 Hz and rolling off quickly for higher and lower frequencies. This is considered in C8 for the Far Term roadmap study. The suppression is applied at all angles and engine conditions.

The over-the-rotor (OTR) acoustic treatment is a technology integrated into the fan casing in the rub strip area that has had successful proof-of-concept demonstrations [19], [20]. The development of this technology is continuing. For the present study, this is designated as C9, and the noise reduction impact of the OTR treatment is predicted by the development of a suppression map, based on past results, that reduces the fan noise component by 0.75 dB in component EPNL.

For the installation of the GTF-like engine on the MFN aircraft, the outer bifurcation away from the fuselage is thin and therefore, only 50% of the available area is used when accounting for the technology in C4. In C11, the outer bifurcation is thickened intentionally in order to increase the available treatment area to the same 75% coverage area as the inner bifurcation. The thickness of the outer bifurcation has not been determined. However, it is expected to be only a few inches thicker, which is deemed acceptable within the framework of this study. The impact of this technology is to increase the attenuation of fan noise in the aft duct by adding more liner area. This is modeled simply by increasing the effective treatment length in the aft duct corresponding to the added liner treatment area.

The effects of these four liner treatments are illustrated in Fig. 6, in terms of the cumulative noise reduction in EPNL, where the colored bars indicate the amount of noise reduction for the four treatments in Table 6. The treatments affect individual noise components so that the noise reduction effects are first shown in the figure for the components, namely, the fan, the core and the jet noise. Then, the effects on the total engine noise and the total aircraft noise are shown. Since the engine noise and the total aircraft noise include components that are not affected by the treatments, such as the jet component for the engine noise and the airframe components for the total aircraft noise, the reduction amounts are smaller than the component reduction, as expected. The jet noise component is not affected by any of the treatments, but it is also included in the figure for completeness. The amount of reduction represented by each color bar is the cumulative value for all three certification conditions. The treatment on the center plug (C8) has the most significant reduction on component noise, more than 9 dB for the core noise component EPNL, approximately 3 dB for each of the three certification conditions. The reduction due to this treatment on the total engine and the total aircraft noise is not as large, because the core noise is not the highest component in the engine noise component ranking, as clearly shown in Fig. 4.

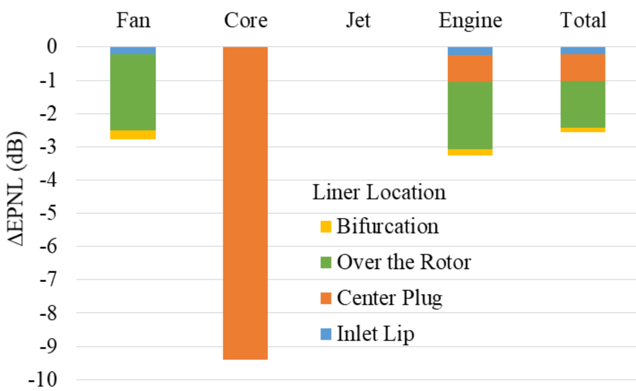

Fig. 6 The impact of engine noise reduction technologies is shown.

V. Airframe Noise Reduction

The airframe noise sources for the MFN aircraft are the landing gear, the leading edge Krueger flap, the trailing edge flap side edges, and the trailing edge noise of the high lift wing. Trailing edge noise is a minor component, and is not considered for noise reduction. For the other three major components, noise reduction concepts are applied to each individually. In the past few decades, there has been significant research and progress in developing airframe noise reduction technologies, some of which have already been included in the Mid Term aircraft studies. Additional technologies, summarized in Table 7, are selected here for the Far Term roadmap. Similar to the numbering of engine noise reduction concepts discussed in the previous section, the discontinuous numbering of the configurations is in order to be consistent with the HWB roadmap study reported in Ref. [1]. Both aircraft have leading edge Krueger devices and landing gear, while trailing edge flaps are absent on HWB but are part of the high lift system for the MFN aircraft. The selected technologies are also illustrated in Fig. 7. For the Krueger noise component, the treatments consist of sealing the Krueger gap, aligning its brackets with the incoming flow, and applying the dual use fairing. For landing gear noise, the technologies include redesigning the main gear with the pod gear concept and 4-wheel configuration and applying a partial fairing on the nose gear. For the flap side edge noise, the technology of continuous mold line design is used. These individual technologies are discussed in detail in the remainder of this section.

Table 7 Airframe noise reduction concepts for Far Term roadmap.

Configuration	*Technology*	*Target Noise*
C12	Sealed Krueger Gap	Krueger Noise at Approach
C13	Krueger Bracket Alignment	Krueger Noise
C14	Duel Use Krueger Fairing	Krueger Noise
C18	Pod Gear	Main Landing Gear Noise
C19	Continuous Mold Line Flap	Flap Side Edge Noise
C21	4-Wheel Pod Gear	Main Landing Gear Noise
C22	Partial Nose Gear Fairing	Nose Landing Gear Noise

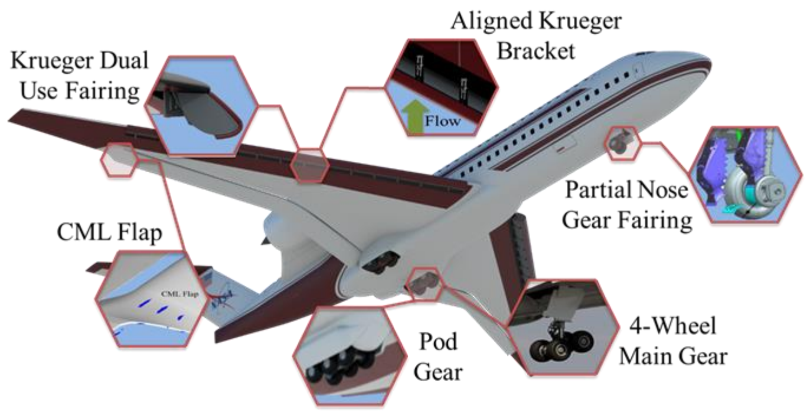

Fig. 7 Illustration of Far Term airframe noise reduction technologies.

Again, the selection of the technology concepts is based on their potential for noise reduction. The sealed Krueger gap is such a concept (C12). This is a concept that has been demonstrated in experimental studies to provide noise reduction for leading edge devices such as slats [21], [22]. Similarly for the Krueger device, sealing the gap between its trailing edge and the main wing can eliminate the high speed flow in the gap and the noise sources associated with the flow, one of the major sources of Krueger noise [14], [23], [24]. The difficulty in implementing this technology is its conflict with the maximum high lift requirement for most conventional aircraft design, which relies on the gap flow to provide the additional lift. This is also how the MFN aircraft was modeled in the earlier iterations in the ERA studies, to have the gap open at approach conditions. Since then, the NASA designers have improved the aerodynamics of this aircraft such that the lift requirements can be met at approach conditions with the Krueger gap sealed. This is certain to benefit the acoustics and thus should be accounted for in the Far Term roadmap. In this case, the prediction tool reported in [14] has the capability to deal with a sealed gap, directly giving the noise levels of the low noise configuration.

The Krueger bracket alignment is also a concept known to reduce noise [25], in this case for the bracket noise subcomponent. It is included as C13 in the present study. Slat and Krueger brackets are conventionally designed to be normal to the leading edge of the wing, for ease of implementation and deployment. This puts the brackets at an angle to the incoming flow, causing cross flow separation around the brackets, and leads to noise generation. The situation is more severe for the Krueger device than slats because a Krueger has more brackets, and each bracket is larger in size and more complex in structure than slat brackets. For slat brackets, experimental data show that up to 3 dB noise reduction is achievable by aligning the brackets with the flow, which can reduce the cross flow separation and hence weaken the noise source strength. The bracket orientation is illustrated in Fig. 8, which shows the underside view of the Krueger device. The upper plot is the conventional design with brackets normal to the leading edge of the wing, and the lower plot has the reoriented brackets aligning with the incoming flow.

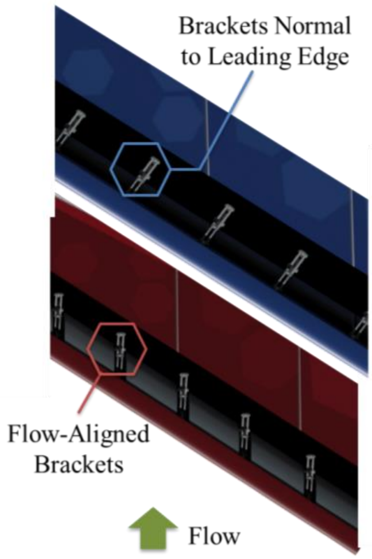

Fig. 8 Illustration of Krueger bracket orientation.

Following the same concept of eliminating or reducing the flow fluctuations around the Krueger device, fairings can be used to streamline the complex structure of the Krueger system, both the Krueger itself and its brackets. This is the concept denoted by C14. It is similar to the concept of the cove filler studied for slats, but the dual use fairing in C14 is designed to target not only the cove flow noise, but also the bracket noise component. The concept is to cover the Krueger cove and the brackets so that they are not exposed to the flow. The additional benefit of this concept is that the brackets do not have to be aligned with the flow, since a large part of the brackets is to be covered by the fairing. This alleviates the practical difficulty of implementation and deployment of brackets in the flow direction. The device is illustrated in Fig. 9, showing the side view of the Krueger system, where the upper plot is the untreated Krueger with both the cove and bracket exposed to the flow, while the lower plot illustrates a fairing that covers both components. To account for this effect and quantify the noise reduction, a process is developed that utilizes the validated prediction capability for cove fillers on conventional slats [26], and the partially validated baseline Krueger prediction capability [14]. By assuming that the slat cove filler and the Krueger dual use fairing both reduce the respective leading edge device to a smooth, streamline body, it is reasonable to assume the low noise levels of the respective smooth, streamline bodies for the two cases are comparable. The difference between the Krueger baseline and the low noise slat configuration then gives the noise reduction for the Krueger dual use fairing. This process of indirectly quantifying the noise reduction is applied here because of the lack of direct experimental data for the dual use fairing on Krueger devices, which needs to be rectified as part of the maturing process for this technology.

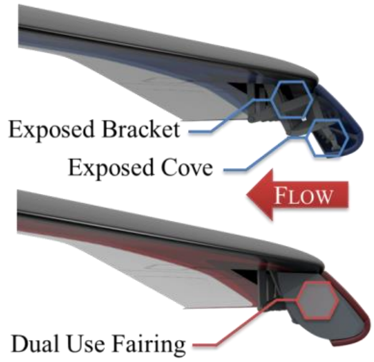

Fig. 9 Illustration of Krueger dual use fairing.

To demonstrate the effects of various treatments on the Krueger noise component, Fig. 10 shows the tone-corrected perceived noise level (PNLT) as a function of the receiving time for the Krueger component for four cases, namely, the baseline Krueger, the cove filler alone applied to the Krueger, the baseline with brackets aligned with the flow, and the application of the dual use fairing. The EPNL values for the four cases are also listed on the figure. It can be seen that the conventional cove filler can reduce the noise by about 1.2 dB for the component EPNL. This is due to the elimination of the flow fluctuations in the Krueger cove region. The noise reduction is mostly in the aft quadrant, as can be expected because the cove noise has a peak directivity normal to the Krueger chord, pointing to the aft quadrant. Aligning the brackets with the flow can reduce the noise almost uniformly in angle, but the reduction is only slightly higher than the cove filler, amounting to a reduction of about 1.6 dB in component EPNL. This is also expected because the bracket noise is more omnidirectional. With the dual use fairing, both the cove and the bracket component are reduced, for a total reduction of about 3.3 dB in component noise.

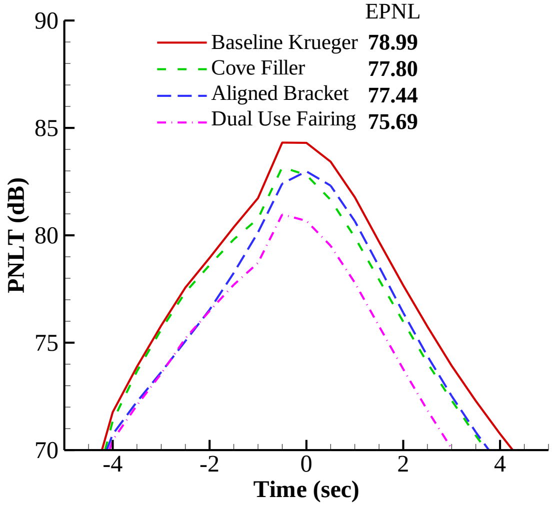

Fig. 10 Effects of treatments on Krueger noise.

For the MFN aircraft, the fuselage-mounted engine configuration presents an opportunity for the most radical noise reduction concept, the pod landing gear, as discussed in Refs. [1], [3]. The concept deviates significantly from conventional transport landing gear installation, but it provides the potential for significant noise reduction. The basic idea is to shorten the height of the main landing gear, feasible because of the reduced requirements on ground clearance due to the fuselage-mounted engines, and relocate the gear closer to the fuselage so that they can be deployed from non-load-bearing pods. The gear itself is unmodified. The shortened gear radiates less noise; however, most of the noise reduction is from two additional effects. First, on approach with gear deployed, the pod shields the gear from the incoming flow like a large fairing to reduce the source strength. Second, the pod traps and attenuates the noise with acoustic treatment on the inside walls of the pod. The pod gear and the conventional gear are illustrated in Fig. 11.

Fig. 11 Comparison between conventional (upper) and pod (lower) landing gear.

The application of the pod gear is included in the present study in C18. It is an important element of the Far Term roadmap because landing gear noise will very likely become a significant, and in some cases, dominant noise component for all the advanced aircraft configurations, as shown in Fig. 4 for the noise component ranking. The pod landing gear is also attractive because other currently studied noise reduction concepts for landing gear can only provide a small amount of incremental reduction that may not be sufficient to meet future requirements on aircraft noise.

To further enhance the attenuation inside the pod, the concept is improved here from its original version proposed in Refs. [1], [3] by partially closing the pod with a toboggan-like device deployed below the axles and brake systems of the gear. With an open pod, the noise from sources inside the pod can be expected to be attenuated significantly, but a large group of sources associated with the axles and brake systems will not be affected because they are outside of the pod and have direct line-of-radiation to the far field observers. The toboggan-like devices block the direct radiation, reflecting the noise back to the pod where the confined space forces the acoustic waves to reflect multiple times from the walls, resulting in additional attenuation from the acoustic liner on the inner surfaces of the pod. This concept is illustrated in Fig. 12 where the pod itself is integrated to the aircraft body, shown by the white colored surfaces, and the toboggan-like device is shown by the orange colored element between the two rows of wheels.

Fig. 12 Illustration of pod gear concept with toboggan.

It should be pointed out that the outer walls of the pod need to be smooth and streamlined to minimize drag at cruise conditions, and the inner walls may also be curved, depending on the detailed design of the pod. The figure visually shows that the noise sources are largely enclosed by the pod and the toboggan-like device. Such a large pod to enclose most of the noise sources is feasible because the pod is non-load-bearing.

The toboggan-like device by itself has been considered as a noise reduction concept for conventional landing gear [13], [27], with the expected benefit of shielding the gear parts from the incoming flow and reflecting the direct radiation from the source upward. Though some wind tunnel tests have measured the effects of the device with varying degrees of noise reduction benefits, flight tests have not shown the expected results in noise reduction. Due to the complex nature of flight tests and the different measurement techniques between wind tunnel and flight tests, it is difficult to conclusively identify the reasons for the unexpected results in the flight tests. In connection to the applications here with the pod gear, two features of the toboggan-like device manifest themselves and are worth further discussion. The first concerns the flow around the toboggan; while it can be understood that the flow right behind the curved part of the toboggan may be slower than that without the toboggan at this location, this is only a small part of the gear assembly. Overall, the toboggan acts as a lifting surface because it is deployed at an angle of attack in reference to the mean flow. Thus, the circulation around it will speed up the flow on the upper side and slow down the flow on the lower side. It is then not clear which part of the gear assembly will experience lower velocity and which part will suffer from higher velocity, due to the deployment of the toboggan, and it is not clear what the aggregate effect will be. The second feature is related to the reflection by the toboggan in the upward direction. With the toboggan alone, the reflected waves will hit the bottom of the wing and then reflect back to the ground. It is then not clear that this upward reflection by the toboggan is indeed beneficial. In the current application, the waves are reflected upwards into the pod, trapped, and dissipated inside the pod.

These effects can be illustrated by the quantitative noise reduction for the main landing gear, which is summarized in Table 8 for the baseline gear, the pod gear, and the pod gear with toboggan. The noise reduction is calculated by a model developed internally for this study that includes noise reflection by the pod gear and toboggan surfaces, dissipation by the liner on the inner walls of the pod, and the local flow velocity decease due to the enclosure. The noise levels listed in the table are the EPNL for the main landing gear component, and acoustic liner treatment is included for both the pod gear and the pod gear with toboggan. The table shows that about 5 EPNL dB noise reduction is achieved by the pod gear, and the reduction is further enhanced by about 2.2 dB by the toboggan device.

Table 8 Landing gear noise reduction by pod gear.

Configuration	*EPNL dB*	*ΔEPNL dB*
Baseline Gear	86.6	-
Pod Gear	81.5	-5.1
Pod Gear with Toboggan	79.3	-7.3

The results in the above table include the effects of noise reduction at all frequencies and all emission angles, as implied by the process of calculating the EPNL noise metric. The reduction as a function of frequency and far field angle is computed by a noise reflection module recently implemented in the landing gear prediction module in ANOPP-Research [28]. An example of this noise reduction is shown in Fig. 13, where the reduction is shown as negative ΔSPL, plotted as a function of the polar and azimuthal angle. The polar angle is defined to be zero at the upstream direction, and the flyover plane is at zero azimuthal angle. The results are for approach conditions at 500 Hz. Clearly, noise reduction is achieved at all radiation angles and is most effective at angles close to the flyover plane.

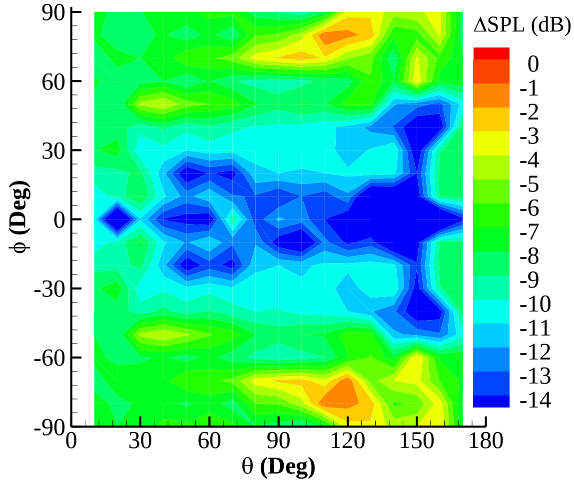

Fig. 13 Predicted noise reduction due to pod gear at 500 Hz.

From the noise component ranking for the baseline MFN aircraft, Fig. 4, it is clear that flap side edges make noticeable contributions to the aircraft noise. There have been a large number of studies in the past on various noise reduction concepts for this noise component. Continuous mold line (CML) flaps is one of them, which is selected here for the Far Term roadmap as C19. The concept results from the understanding of the source mechanisms for the flap side edge noise, namely, the rollup vortex in the cross flow at the side edge. The CML flap intends to prevent or reduce this rollup vortex, and hence, reduce the noise associated with it. An illustration of this concept is given in Fig. 14, taken from [29], where the left plot is a conventional baseline flap side edge, while the right plot has a CML that smoothly transitions the geometry from the main wing to the flap. The contours in the figure are the amplitude of the turbulence kinetic energy in the rollup vortex, the flow feature responsible for the noise generation. For the baseline flap, the rollup vortex is clearly seen in the side edge region, and the high amplitude turbulence fluctuations are present. For the CML flap on the right, the rollup vortex is essentially eliminated, and the remaining fluctuations are of much smaller amplitude.

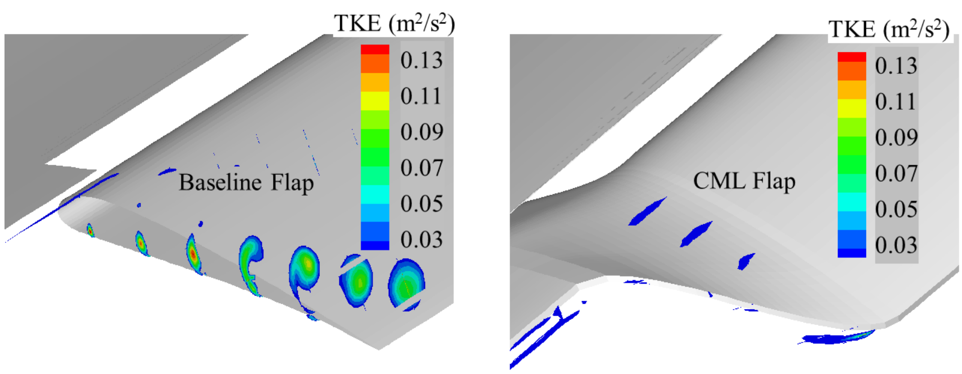

Fig. 14 Illustration of continuous mold line technology.

Based on the source mechanisms of flap side edge noise, for both the baseline flap and the CML flap, a model is developed to quantify the reduction. This model targets the two flap side edge noise components, with the low frequency component scaling on the flap chord length and the high frequency component on the flap thickness. From small scale wind tunnel test data [30], maximum reduction is established at the peak frequencies and peak radiation angles of the two noise components. A functional falloff from the peak values is then developed to calculate the reduction as a function of frequency and directivity angle. An example is shown in Fig. 15 where the noise reduction at 500 Hz is plotted as a function of the polar and the azimuthal angle. Clearly, significant noise reduction is seen in the forward quadrant in the direction of peak radiation for flap side edge noise.

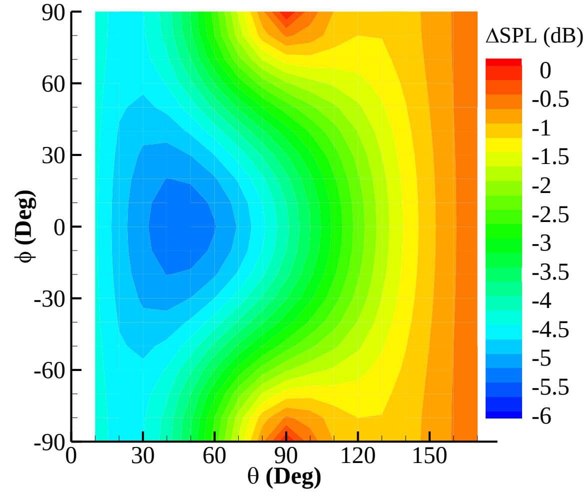

Fig. 15 CML noise reduction at 500 Hz.

The next configuration, C21, is a simple change of design for the main landing gear, from a 6-wheel assembly to a 4-wheel assembly. The large twin aisle class of aircraft in the NASA portfolio were designed with 6-wheel main landing gear because the reference vehicle was the Boeing 777. A 6-wheel main gear may not be the optimal choice for advanced vehicles. To see this, Table 9 compares the main landing gear configurations for some wide body aircraft that have entered into service in recent years, together with the MFN aircraft. From the relation of gear type and aircraft weight, it is clear that a 4-wheel main gear should be sufficient for the MFN aircraft, because heavier aircraft have used 4-wheel gear with comparable sizes. The change of the number of wheels from 6 to 4 will likely reduce the weight of the gear assembly, but the most significant benefit is probably the reduced noise.

Table 9 Comparison of main landing gear.

Aircraft	*MTOW* (lb)	*Wheels per Gear*	*Tire Diameter* (in)	*Tire Width* (in)
A350-900	617295	4	55	21
A350-1000	685638	4	50	20
B787-8	502500	4	50	20
B787-9	560000	4	52	21
MFN	542837	6	50	20

By combining the pod gear concept discussed in configuration C18 and the 4-wheel configuration C21, an approach for main landing gear noise reduction is to use a 4-wheel pod gear. The combined effects are illustrated in Fig. 16, which plots the PNLT values of the main gear noise component for four configurations, namely, the 6-wheel baseline, the 4-wheel baseline, the 6-wheel pod gear, and the 4-

wheel pod gear. The EPNL values for the four configurations are also shown in the figure. The combined effects of wheel redesign and the pod gear concept give 11.4 dB component EPNL noise reduction, of which approximately 7.5 dB results from the pod gear, and the remaining from the redesign.

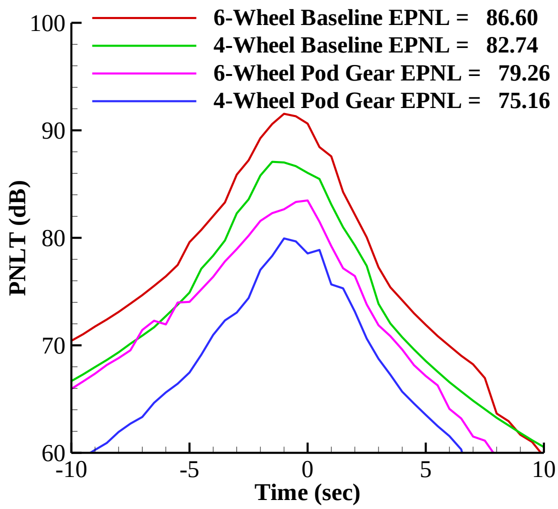

Fig. 16 Main gear noise reduction.

The last technology for airframe noise reduction is a partial fairing on the nose gear, included in C22. The concept of landing gear fairings is actually a Mid Term technology, likely to mature for practical implementation before 2035. It is considered here for the Far Term roadmap because as the noise levels of the other components are lowered, the nose gear may no longer be a negligible component, and noise reduction on this component might have more impact on the total aircraft noise.

In Fig. 17, the component noise reduction from each technology is shown by the colored bars. Since none of the technologies is targeting the minor component of trailing edge noise, the reduction for this component is zero, but it is included in the figure for completeness. The two columns after the trailing edge column are the total airframe and total aircraft noise, showing the accumulative effects of the component reductions. The impact of the component reductions to the total airframe noise is weighted by the ranking order of the component sources, and the impact to the total aircraft noise is further weighted down by the engine noise components.

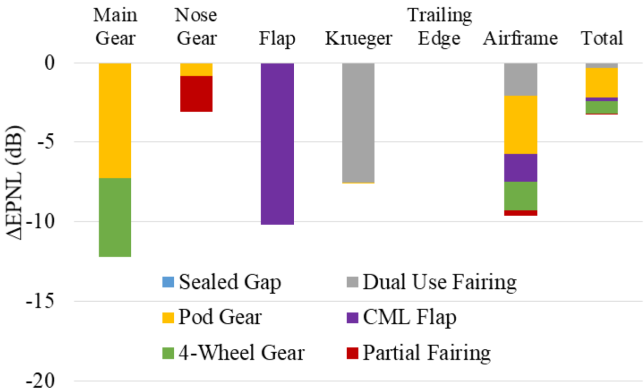

Fig. 17 Airframe noise reduction.

It should be pointed out that the color bars in the figure represent the cumulative noise reduction of the three certification conditions for components that are present at all three conditions. For example, the CML noise reduction for flap side edge noise benefits all three conditions, and the cumulative reduction is about 10 dB. Of course, landing gear noise reduction comes only from approach conditions because it is absent at the other two conditions. Most of the technologies benefit only one noise component, except for the pod gear, in which case the redesign of the gear shortens the total lengths of both the main and the nose gear, so that the nose gear noise is also reduced.

VI. MFN Far Term Configuration System Noise

Table 10 summarizes all configurations, including five cases with prediction improvements, four cases with engine noise reduction concepts, and seven cases with airframe noise reduction concepts.

Table 10 Summary of roadmap configurations.

Configuration	*Description*	*Component*
C0	Baseline from Mid Term Study	-
C1	Gear Strut Correction	Landing Gear
C2	Tuned Duct Liner	Inlet Fan
C3	Inter-Stage Liner	Aft Fan
C4	Bifurcation Liner	Aft Fan
C5	Prediction Tool Update	Airframe
C7	Inlet Lip Liner	Inlet Fan
C8	Center Plug Liner	Engine Core
C9	Over-the-Rotor Liner	Fan
C11	Increased Outer Bifurcation Liner	Aft Fan
C12	Sealed Krueger Gap	Krueger at Approach
C13	Aligned Krueger Bracket	Krueger
C14	Krueger Dual Use Fairing	Krueger
C18	Pod Gear	Main Landing Gear
C19	Continuous Mold Line Flap	Flap
C21	4-Wheel Pod Gear	Main Landing Gear
C22	Partial Nose Gear Fairing	Nose Gear

The predicted noise levels in terms of the cumulative EPNL for all the configurations are shown in Table 11. The last column in the table gives the margin of the cumulative noise levels for each configuration in reference to the Stage 4 certification limit, which is 294.2 dB for the MFN aircraft, as shown in Table 2. Since the first 5 configurations are improvements in the predictions and are not noise reduction, they are not included in the noise reduction table. The noise margin for the cumulative EPNL shown in the table gradually increases with the configuration number because this is the sequential buildup, adding one technology and including the benefits of all prior configurations. This process is followed unless there is a conflict between the technology to be added and one already included in the calculation, or the noise reduction benefits of the two are not additive. In this case, only the one with larger noise reduction is kept in the technology buildup. An example is the Krueger bracket alignment denoted by C13, whose noise reduction becomes unrealizable once the Krueger dual use fairing is used, designated by C14, because the covered brackets become insensitive to the orientation in noise generation. The bracket noise reduction is also partially provided by the dual use fairing. Thus, the final technology suite includes the dual use fairing, but not the aligned brackets. Similarly, the final configuration includes the 4-wheel pod gear, but not the 6-wheel pod gear.

Table 11 Noise reduction buildup.

Configuration	*Description*	*Cumulative EPNL* (*dB*)	*EPNL Margin to Stage 4* (*dB*)
C5	Prediction Tool Update	259.9	34.3
C7	Inlet Lip Liner	259.7	34.5
C8	Center Plug Liner	258.9	35.3
C9	Over-the-Rotor Treatment	257.5	36.7
C11	Increased Outer Bifurcation Liner	257.3	36.9
C12	Sealed Krueger Gap	257.3	36.9
C13	Aligned Krueger Bracket	257.2	37.0
C14	Krueger Dual Use Fairing	256.9	37.3
C18	Pod Gear	255.1	39.1
C19	Continuous Mold Line Flap	254.8	39.4
C21	4-Wheel Pod Gear	254.0	40.1
C22	Partial Nose Gear Fairing	254.0	40.2

The overall noise levels for the final configuration, C22, including all the prediction improvements and the relevant noise reductions, are shown in Table 12 in terms of EPNL at the three certification conditions, together with the cumulative value. These are given in the first data row. For comparison, the corresponding noise certification limits for Stage 4 are listed in the second row, which lead to the respective margins in the third row. The cumulative margin is 40.2 dB to Stage 4, which can be compared with the NASA noise goal set for this Far Term time frame, given in the last row in the table.

Table 12 MFN aircraft EPNL with Far Term technology.

	Approach	*Cutback*	*Sideline*	*Cumulative*
MFN (C22)	87.0	83.3	83.7	254.0
Stage 4 Limit	104.6	98.4	101.2	294.2
Margin to Stage 3	17.6	15.1	17.5	50.2
Margin to Stage 4	-	-	-	40.2
NASA Far Term Goal	-	-	-	42 - 52

To explicitly reveal the reductions of various technologies on the noise components, the differences in the noise levels between the final configuration, C22 and the starting point configuration, C5, are plotted in Fig. 18, for all the components at the three certification conditions. For a single component at a single condition, the main landing gear noise is reduced the most, by 11.4 dB with approximately 7.5 dB from the pod gear concept and the remaining from the redesign of the gear from a 6-wheel to a 4-wheel configuration. The other components have smaller single-condition reduction, but the cumulative reduction can be comparable. This is more clearly shown in Fig. 19, which plots the component noise reduction for both the individual certification conditions and the cumulative levels. Of the components considered here, cumulative noise of the main landing gear, the flap side edge, the Krueger device and the engine core noise are all significantly and comparably reduced, with amounts varying from more than 7 to above 12 dB. The rest of the components have little to no reductions. The small amount of noise reduction for the fan component is the reason it is the component holding up the overall noise levels of the final configuration, as will be discussed in the next section.

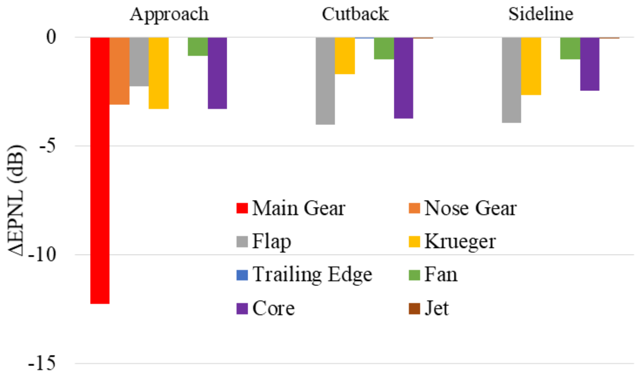

Fig. 18 Component noise reduction at certification conditions.

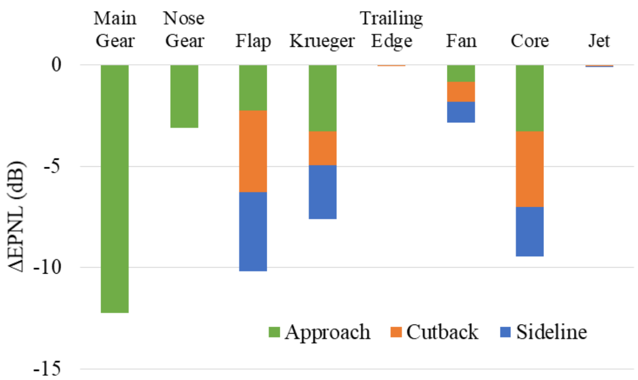

Fig. 19 Cumulative component noise reduction due to Far Term technologies.

VII. MFN Far Term Technology Roadmap

The impact of each technology is quantified on the most equivalent basis by performing the one-off analysis in which the final configuration, C22, is taken as the starting point, and one at a time, a single technology is removed to quantify the change in noise levels due to this technology. The process is repeated for all the technologies in the final configuration, always with only one technology removed from the collection. This leads to the results shown in Table 13, where the first column lists the individual technology taken off in the calculation, the second column shows the aircraft EPNL margin to Stage 4 for these one-off configurations, and the last column gives the noise impact of the individual technologies in cumulative EPNL values. It can be seen that the first three technologies in the table are carried over from the Mid Term configuration. They are included here because once additional noise reduction is applied to the aircraft, the ranking order and the amplitudes of the component noise change, which in turn affects the effectiveness of the noise reduction implemented previously. Thus, the noise reduction impact needs to be recalculated. This effect can either enhance or degrade the noise reduction benefit. By comparing the results with those in Fig. 2, for example, the effects of the MDOF liner are enhanced from about 2 dB to 2.4 dB, while the benefit of soft vane liner is decreased from about 1.4 to

1.0 dB. The most significant change is in the total PAA effect, with a reduction enhancement from 2.3 to 4.7 dB. This is due to the dominance of the fan noise component. The noise reduction of other components in the Far Term configuration makes the dominance even more profound, leading to the large noise impact of 4.7 dB for this technology. Some of the change is also attributed to the improvements in calculating the total PAA effect of the MFN.

Table 13 Impact of individual technology on cumulative EPNL.

Technology	*EPNL Margin to Stage 4 (dB)*	*EPNL Noise Impact (dB)*
MDOF Liner	37.8	2.4
Soft Vane Liner	39.2	1.0
PAA Effects	35.5	4.7
Inlet Lip Liner	40.0	0.2
Center Plug Liner	39.4	0.8
Over-the-Rotor Treatment	38.6	1.6
Increased Outer Bifurcation Liner	40.1	0.1
Sealed Krueger Gap	40.2	0.0
Dual Use Krueger Fairing	39.6	0.6
Continuous Mold Line Flap	39.6	0.6
4-Wheel Pod Gear	38.0	2.2
Partial Nose Gear Fairing	40.1	0.1

The impact of the individual technologies on the total aircraft noise shown in the above table reveals the relative importance of the individual technologies. From these predicted values, the technologies can be categorized according to their respective efficiency in noise reduction, as shown in Table 14. The most effective group of technologies includes the total PAA effect, the MDOF liner and the 4-wheel pod gear, giving an average of 3.1 dB noise reduction in cumulative EPNL. The next category in the table has five technologies, all with substantial noise reduction with average impact of 0.9 dB in EPNL. These two categories of technologies contribute essentially all the noise reduction to the final configuration, and thus, logically form the most effective noise reduction roadmap. The other two groups of technologies in the table, termed “Small” and “Not Used”, are screened out of the roadmap, the former because of the small amount of noise reduction and the latter due to conflict with other technologies that are already in the roadmap and have better noise reduction benefits.

Table 14 Technology category by noise rediction efficiency.

Reduction	*Technology*	*EPNL Impact (dB)*
Significant	• PAA Effects	4.7
	• MDOF Liner	2.4
	• 4-Wheel Pod Gear	2.2
Substantial	• Soft Vane Liner	1.0
	• Center Plug Liner	0.8
	• Over-the-Rotor Liner	1.6
	• Dual Use Krueger Fairing	0.6

	• Continuous Mold Line Flap	0.6
Small	• Inlet Lip Liner • Increased Outer Bifurcation Liner • Sealed Krueger Gap • Partial Nose Gear Fairing	~0.0
Not Used	• 6-Wheel Pod Gear • Krueger Bracket Alignment	-

The relative component noise levels for the final configuration C22 are shown in Fig. 20. It is especially useful to examine this in light of the fact that the result is still a few decibels short of the NASA goal. This figure can be compared with Fig. 4, which is for the starting configuration, plotted in the same format and in the same scale so that the effects of the noise reduction technologies are clearly revealed. The noise reductions not only lower the amplitudes of the noise components, but also alter the rank order. It is immediately clear that the holdup for the overall noise levels of the final configuration is the fan noise, which is about 5 to 8 dB higher than the other components at the three certification conditions. Another noticeable feature of Fig. 20 is that, except for the fan noise component, the components are all comparable in amplitudes, separated from each other usually by a few decibels.

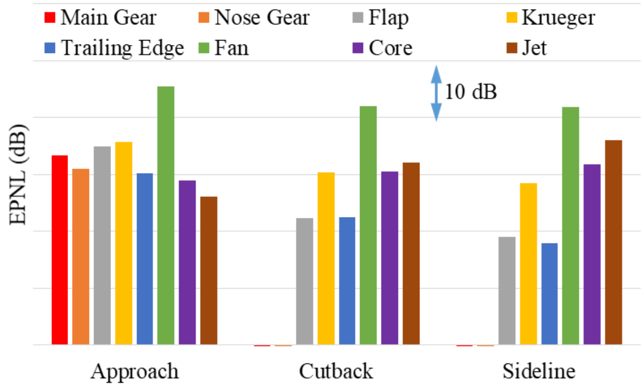

Fig. 20 Noise component ranking for the Far Term (C22) MFN aircraft.

VIII. Summary

A noise reduction technology roadmap for the MFN aircraft has been developed for the NASA defined Far Term time frame beyond 2035, based on ground-up predictions from components to total aircraft noise. The predictions have utilized the most advanced capabilities in the NASA ANOPP-Research code and have included noise reduction potentials of various technologies. The system noise assessment has been enabled by updated component source predictions, PAA models from experimental data and numerical computation, and noise reduction models developed from currently available test data to cover important parametric variations in frequency and directivity angles.

Some of the technologies in this roadmap have been studied in the past, such as the various types of liner treatments in the engine, while others are concepts newly conceived in recent years, resulting from unique features of the advanced aircraft configuration. These concepts include the Krueger dual use fairing and the pod gear. Both are prompted by the need for reducing the main noise components of the MFN aircraft, and both utilize features of the aircraft. Since these concepts have been proposed only recently, there are no test data yet, and the roadmap study presented here has relied on physics-based system level methods to quantify the noise reductions. Refined aircraft configuration, detailed design, and experimental demonstration of noise reduction are clearly much needed as the next steps to develop and mature these technologies.

The final configuration in this roadmap study has been shown to have the potential to reach noise levels that are about 40.2 dB below the noise certification regulation of Stage 4, in terms of the cumulative EPNL. This is accomplished by two groups of technologies. The first group has significant noise reduction potential on the aircraft system level and includes the total aircraft PAA effects such as shielding, diffraction, and reflection (4.7 dB) and the technologies of MDOF liner (2.4 dB) and the 4-wheel pod gear (2.2 dB). The second group can also provide substantial system noise reduction and contains the soft vane liner (1.0 dB), the center plug liner (0.8 dB), the over-the-rotor liner (1.6 dB), the dual use Krueger fairing (0.6 dB), and the continuous mold line flap (0.6 dB). These two groups of technologies should logically be the focus of efforts to develop and mature noise reduction for the MFN aircraft.

The noise levels of the final configuration have been shown to be held up by fan noise at all three certification conditions. Since the engine noise is aft fan dominant and the MFN has significant noise benefit from the wing and fuselage PAA effects, the high levels of fan noise in the final configuration are mostly aft fan noise. Thus, to achieve further noise reduction, innovative concepts for aft fan noise reduction would have the most impact. In general, this can be achieved by fan source noise reduction such as low noise blade design, additional improvements in acoustic liner technology applied in the duct for specific applications such as the soft vane, and design modifications to the aft of the aircraft configuration to maximize the total noise reduction from the combined PAA effects of acoustic scattering, diffraction, and flow interactions.

Acknowledgments

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