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# Mixed-Fidelity Approach for Design of Low-Boom Supersonic Aircraft

Wu Li*
*NASA Langley Research Center, Hampton, Virginia 23681*
Elwood Shields†
*Alliant Techsystems, Inc., Hampton, Virginia 23681*
and
Karl Geiselhart‡
*NASA Langley Research Center, Hampton, Virginia 23681*

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**This paper documents a mixed-fidelity approach for the design of low-boom supersonic aircraft with a focus on fuselage shaping. A low-boom configuration that is based on low-fidelity analysis is used as the baseline. The fuselage shape is modified iteratively to obtain a configuration with an equivalent-area distribution derived from computational fluid dynamics analysis that attempts to match a predetermined low-boom target area distribution and also yields a low-boom ground signature. The ground signature of the final configuration is calculated by using a state-of-the-art computational-fluid-dynamics-based boom analysis method that generates accurate midfield pressure distributions for propagation to the ground with ray tracing. The ground signature that is propagated from a midfield pressure distribution has a shaped ramp front, which is similar to the ground signature that is propagated from the computational fluid dynamics equivalent-area distribution. This result supports the validity of low-boom supersonic configuration design by matching a low-boom equivalent-area target, which is easier to accomplish than matching a low-boom midfield pressure target.**

## Nomenclature

$A_e$ = equivalent area
$dp/p$ = (the calculated pressure: the ambient pressure)/(the ambient pressure)

## I. Introduction

ALTHOUGH designing an efficient supersonic cruise aircraft is not a simple task, it can be created by designing an aerodynamically efficient wing, optimizing the wave drag with fuselage shaping, and mitigating interference problems caused by component integration with local modifications that use computational fluid dynamics (CFD) analysis. To create a low-boom aircraft, not only must some measure of aerodynamic efficiency be retained, but the shapes of the various components along with the lift characteristics must be integrated in a manner that creates an acceptable pressure signature many body lengths away from the configuration. This is truly a multidisciplinary design problem and, ideally, a multidisciplinary design optimization tool should be used to reshape a baseline configuration into a low-boom design. However, critical technologies such as an adjoint solver for determining the sensitivity of the midfield pressure distributions with respect to shape changes is not available for a complete aircraft.

This paper documents the use of a mixed-fidelity approach for the design of low-boom supersonic aircraft with a focus on fuselage shaping to minimize the difference between a CFD equivalent area $A_e$ of the configuration and a predetermined low-boom target $A_e$.

The mixed-fidelity approach is based on two recent advances in supersonic concept design and analysis: the inverse design optimization of low-boom supersonic concepts with smoothest fuselage shape modifications [1] and the integration of automated CFD analysis in conceptual design of supersonic aircraft [2]. The first capability allows one to reshape the fuselage smoothly to obtain a configuration with an $A_e$ distribution that matches a low-boom target. Because multiple iterations are required to match the total $A_e$ distribution of a supersonic concept with a low-boom target $A_e$ distribution, all of the analyses involved in the previous inverse design cases are low-fidelity methods (i.e., codes that finish calculations in seconds). See [1] for more detailed descriptions and additional references for these low-fidelity methods. Automated CFD analysis allows a low-boom concept that has been designed with low-fidelity analyses to be refined by revealing the additional characteristics in the $A_e$ distribution that could not be detected by the low-fidelity analyses. The mixed-fidelity approach integrates the CFD $A_e$ analysis into the fuselage shaping process that is documented in [1] to refine the low-fidelity design so that the CFD $A_e$ distribution of the refined design is closer to a low-boom target $A_e$. Several refinement steps may be necessary to obtain a configuration with a CFD $A_e$ distribution that is close enough to the low-boom target $A_e$ to yield a low-boom ground signature. The mixed-fidelity low-boom design method has been implemented in ModelCenter [3], which enables a conceptual designer with limited CFD knowledge to match the CFD equivalent-area distribution to the target within a few days starting from a low-fidelity, low-boom baseline.

In theory, the validity of designing a low-boom configuration by matching a predetermined target is based on the following far-field theory assumption: the complete aircraft configuration can be treated as an axisymmetric body of revolution. This body of revolution matches the Mach angle cut area distribution due to volume and lift for the roll angle directly below the configuration (see [4] for a survey of sonic boom theory). Even though the nonsymmetrical three-dimensional effects of a complete aircraft with nacelles and tails may not rigorously fit this assumption, this mixed-fidelity method for CFD $A_e$ matching can be shown to yield a configuration with the front portion of the ground signature shaped when the signature is

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*Senior Research Engineer, Aeronautics Systems Analysis Branch, Mail Stop 442.
†Senior System Engineer, Space Division.
‡Aerospace Engineer, Aeronautics Systems Analysis Branch, Mail Stop 442.

propagated from a CFD offbody pressure distribution. This provides empirical evidence of the validity of this mixed-fidelity CFD $A_e$ matching instead of midfield pressure matching, at least for the front portion of the signature.

The CFD ground signatures of the final low-boom designs are calculated by using a CFD boom analysis method developed by Li et al. [2] and Campbell et al. [5], which has been implemented in the ModelCenter process. The ModelCenter CFD boom analysis can be set up by specifying a few parameters (such as cruise Mach number, flight altitude, cruise lift coefficient, location of the midfield pressure distribution, etc.). Then the CFD boom analysis can be run in ModelCenter and the ground signature that is propagated from the CFD pressure distribution at 3 to 10 body lengths below the configuration can be obtained within 8 to 12 h by using 48 Linux cluster processors.

Note that a predetermined low-boom target $A_e$ might not be realizable for a feasible aircraft configuration. The target $A_e$ distribution was chosen to meet volume constraints and does not match the maximum $A_e$ value due to the lift of the configuration. This is a limitation of the method used to develop the target $A_e$. At the present time, no documented method exists for generating a realizable target $A_e$ with both a well-shaped front and aft portions of the ground signature that will also meet the necessary volume constraints. Reference [6] documents one attempt to use numerical optimization methods to generate realizable low-boom $A_e$ distributions. Some preliminary results show that tail lift is an effective approach for shaping the aft portion of the ground signature of a low-boom configuration. Therefore, the tail lift is also used here to help tailor the aft portion of the ground signature. However, the design of a low-boom configuration that has both front and aft shaped portions of the ground signature propagated from the midfield pressure distribution is an area for further development and is beyond the scope of this paper.

The remainder of the paper is organized as follows. Section II includes the details of the mixed-fidelity fuselage shaping process for low-boom design. In Sec. III, the mixed-fidelity low-boom fuselage shaping process is demonstrated with a supersonic business jet design case. The verification results of the mixed-fidelity designs are given in Sec. IV. The final section contains the concluding remarks.

## II. Mixed-Fidelity Low-Boom Fuselage Shaping Method

The mixed-fidelity design process is a refinement of the low-fidelity low-boom design process, which is described in [1], by including automated CFD analysis. The details for the automated CFD analysis process can be found in [2]. The manual script execution portion of the automated CFD analysis process that is described in [2] also has been integrated in ModelCenter; an automated USM3D [7,8] can be run within ModelCenter for either aero analysis or boom analysis (by using SSGRID [4], which is a grid stretching code for high grid resolution up to ten body lengths below the configuration). The process is completely automated and controlled by only a few user input parameters. The process starts from the conceptual geometry of a complete supersonic aircraft, converts the aircraft geometry to a watertight CFD geometry in VGRID [9,10] format, generates sources for grid generation based on a few intuitive control parameters, uses VGRID for unstructured grid generation, uses SSGRID to shear and stretch the volume grid for improved boom prediction, and runs USM3D to obtain a CFD Euler solution. PCBOOM [11], a boom analysis code that uses ray tracing, is also integrated in ModelCenter to propagate the offbody pressure distributions to the ground. This provides a seamless process for running either CFD $A_e$ analysis or CFD boom prediction for a supersonic concept with a turnaround time of 2 or 12 h, respectively, with the use of 48 Linux cluster processors. The average unstructured grid sizes for CFD $A_e$ analysis and CFD boom prediction are approximately 6 million and 15 million cells, respectively. The CFD $A_e$ is calculated by using the formulas described in [4]. The $A_e$ due to lift is calculated by using the CFD surface pressure distribution and the $A_e$ due to volume is calculated by using the far-field wave drag Mach angle cut area methodology on the unstructured surface mesh. The code for calculating CFD $A_e$ is called "gacunst," which is developed by Don Howe at Gulfstream.

The automated CFD analysis process enables the use of CFD $A_e$ distribution during the low-boom fuselage shaping process instead of the $A_e$ distribution that is calculated with the use of low-fidelity methods. However, using CFD $A_e$ analysis to calculate the $A_e$ distribution each time the fuselage shape is changed is too time consuming. Therefore, the following mixed-fidelity $A_e$ is used for fuselage shaping:

$$A_e^{\text{mixed}} = A_{e,\text{CFD}}^{\text{total}} - A_{e,\text{old}}^{\text{fuse}} + A_{e,\text{new}}^{\text{fuse}}$$

In the above formula, the equivalent areas for fuselage $A_{e,\text{old}}$ and $A_{e,\text{new}}$ are calculated by using the low-fidelity analysis that is documented in [1]. That is, the fuselage $A_e$ distributions are calculated by using the fuselage as a standalone component without consideration for the volume difference that results from the intersection between the fuselage and other components of the configuration (such as the wing, the pylon, and the vertical tail). Moreover, the $A_e$ difference that is caused by lift for the two configurations is not accounted for in the mixed-fidelity $A_e$. In other words, the mixed-fidelity approach is based on the assumption that the (low fidelity) $A_e$ difference between the two fuselage shapes is a reasonably accurate estimate of the actual difference in the (high fidelity) CFD $A_e$ distributions of the two configurations.

The mixed-fidelity fuselage shaping process is also implemented in ModelCenter. The goal of this process is to obtain a new fuselage shape that reduces the difference between the mixed-fidelity total $A_e$ and the low-boom target $A_e$ as much as possible while still retaining the practical aspects of the configuration. Here, the practical aspects of the configuration are based on some simple rules used by the designer, such as enough fuselage volume for cabin space, some volume requirement for structural support, and the visual smoothness of overall fuselage shape, etc. This requires some judgment on the part of the designer as to how much of the target $A_e$ should be matched. In most cases, this is determined when the front portion of the ground signature that is propagated from the mixed-fidelity total $A_e$ distribution has been matched accurately with that of the target signature. At this point, the CFD equivalent area of the modified configuration is calculated by running the CFD $A_e$ analysis and comparing the results again to the target $A_e$. Then this modified configuration will be used as the starting point for another iteration of mixed-fidelity fuselage shaping. This process is repeated until the perceived loudness level of the shaped ground signature no longer decreases when the CFD equivalent area is used in the boom analysis. Then the CFD analysis is applied to the final configuration to obtain a midfield pressure distribution that is propagated to the ground by ray tracing. This verifies whether the configuration indeed has a shaped low-boom ground signature. Figure 1 provides an overall view of the mixed-fidelity low-boom configuration design process, along with the related low-fidelity design and high-fidelity verification.

## III. Case Study

A previously designed supersonic business jet configuration, shown in Fig. 2, is used as a starting point to demonstrate the mixed-fidelity low-boom fuselage shaping process. The configuration is developed to achieve the best performance, expressed as maximum range, for a given takeoff gross weight of 100,000 lb and a balanced field length of 7000 ft. The cabin is to be equivalent to that of a Citation X, and the cruise Mach number is 1.8. The aircraft length is 170 ft. This configuration is designed at the conceptual level by using low-fidelity analysis codes to satisfy the practical considerations of the various disciplines, such as aerodynamics, structures, systems, low-speed performance, stability and control, and landing-gear placement. The details for the low-fidelity low-boom design process can be found in [1].

The baseline was designed to match as much of the target $A_e$ as possible while still trying to maintain the practical aspects of the configuration. This was possible up to an effective distance of

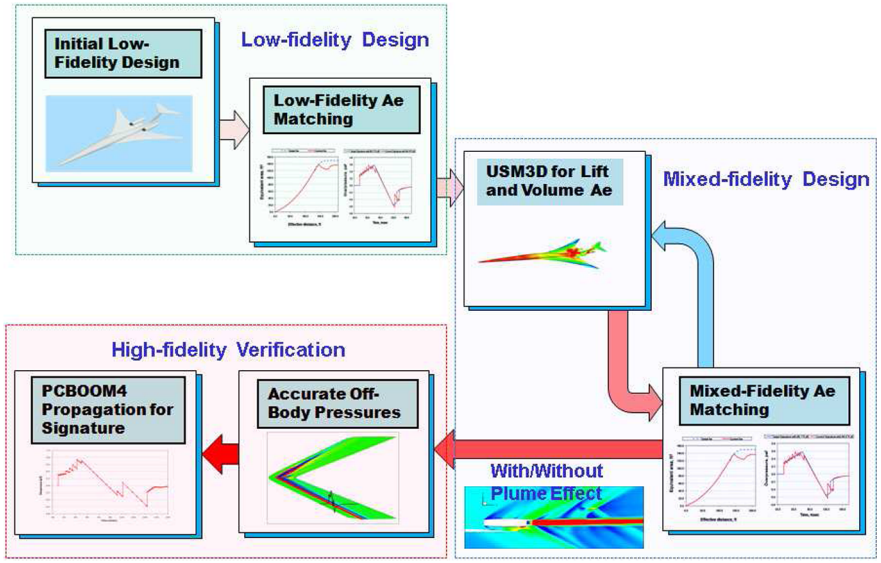


**Fig. 1 Flowchart of the mixed-fidelity design and analysis process.**

approximately 145 ft and resulted in a good match of the forward portion of the ground signature (see Fig. 3). The $A_e$ value of 136 ft$^2$ for the configuration at $Xe \geq 192$ ft is completely determined by the flight condition (*i.e.*, the cruise weight, altitude, and speed) and is lower than the corresponding value of the target $A_e$. It was necessary to generate a low-boom ramp target $A_e$ for a higher cruise weight in order to have enough $A_e$ volume for the configuration. As a consequence, it is impossible to match the aft part of the target $A_e$ at the current cruise weight. No effort has been made to shape the aft signature. Instead, tail lift was used in an attempt to shape the aft portion of the ground signature. An incidence of 2.5 deg was added to the horizontal tail and this changed the aft portion of the signature so that it was no longer an $N$-wave. At this point, additional changes to the configuration that could potentially improve the matching of the target $A_e$ were considered and it was determined that they would have an adverse impact on the configuration's performance or require new technologies in other disciplines such as structures. The complete low-fidelity low-boom design process resulted in a significant decrease in the perceived loudness of the baseline configuration from 91.8 to 84.5 PLdB. The low-fidelity $A_e$ matching and ground signature analysis results of the baseline are shown in Fig. 3.

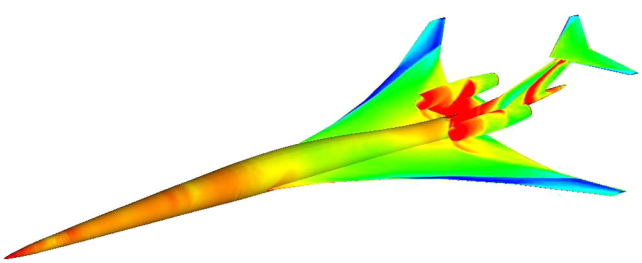

**Fig. 2 Baseline supersonic concept.**

Next, a CFD analysis is run. A comparison of the CFD $A_e$ distribution of the baseline with the low-fidelity $A_e$ distribution shows significant differences (see the left plot in Fig. 3). The front portion of the ground signature from the CFD $A_e$ distribution exhibits a significant shock of 0.4 psf, which leads to a 40% increase in the maximum overpressure over that of the low-fidelity ground signature, and a pronounced change to the aft portion of the signature (see the right plot in Fig. 3). As a result, the ground signature for the CFD $A_e$ has an almost 5 PLdB increase in the perceived loudness over the low-fidelity signature. These discrepancies demonstrate the value of using CFD analysis in the low-boom supersonic configuration design.

Three iterations of mixed-fidelity fuselage shaping were applied to the baseline to obtain a configuration for which the CFD $A_e$ matched the target $A_e$ for $Xe \leq 130$ ft and a front-shaped ground signature was maintained. The analysis results are shown in Figs. 4–6.

In each of the mixed-fidelity iterations, the equivalent area from the CFD analysis that is attributable to lift remains the same, and the total mixed-fidelity $A_e$ changes only because of changes in the fuselage volume distribution, as detailed in Sec. II. The changes to the fuselage volume are accomplished by using the optimization and smoothing tools, such as BOSS [1]. BOSS is used to modify the radius distribution of the fuselage at 100 or more longitudinal locations for reducing the discrepancies between the mixed-fidelity

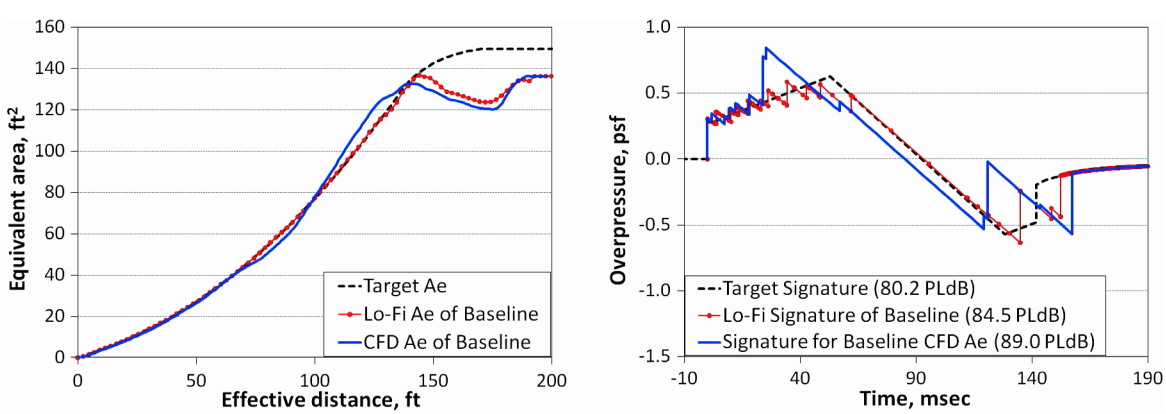


**Fig. 3 $A_e$ and ground signature analysis of the baseline.**

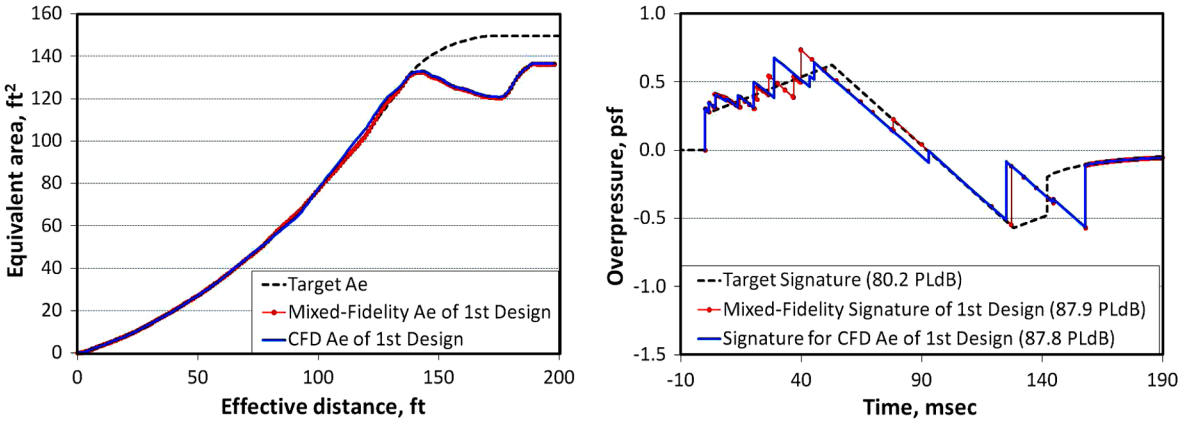


**Fig. 4 $A_e$ and signature analysis of the first mixed-fidelity design.**

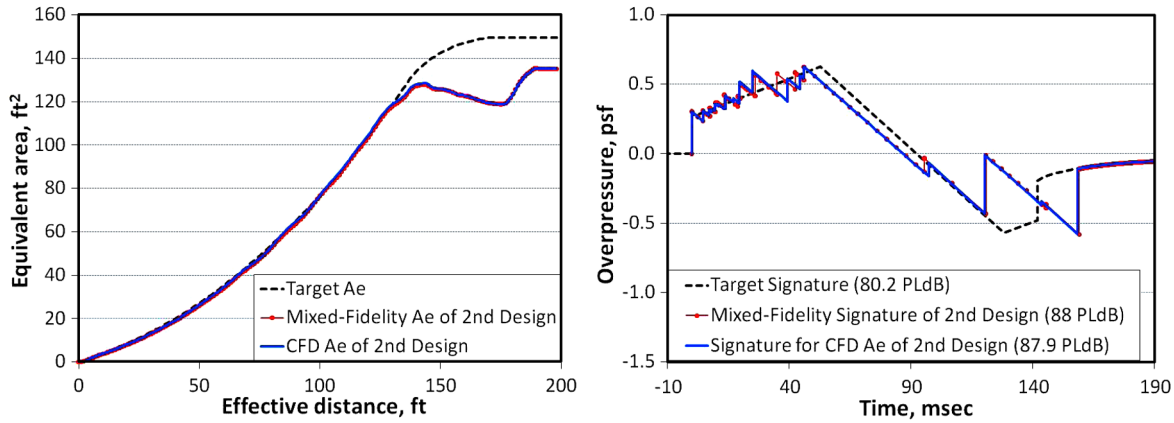


**Fig. 5 $A_e$ and signature analysis of the second mixed-fidelity design.**

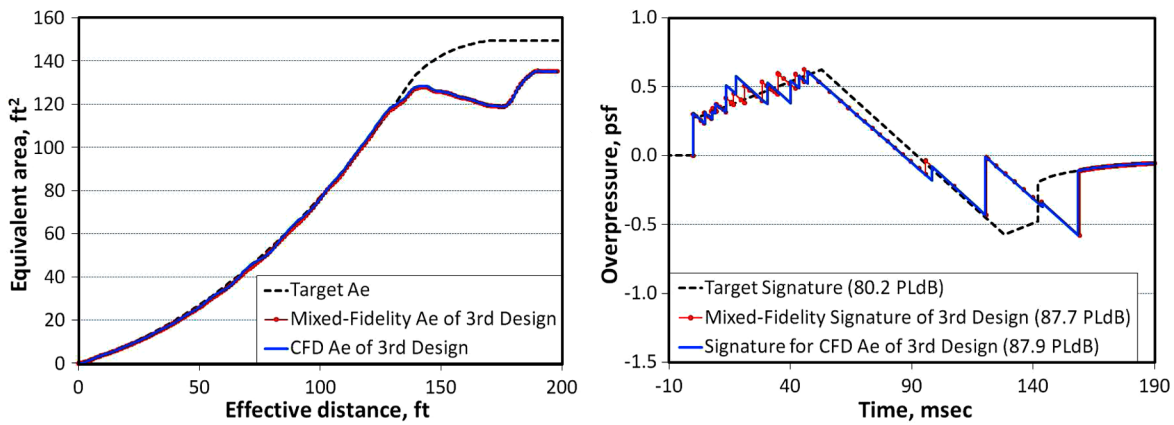


**Fig. 6 $A_e$ and signature analysis of the third mixed-fidelity design.**

and target $A_e$ distributions. Each iteration is completed when the match between the mixed-fidelity $A_e$ and the target $A_e$ is close enough to create a front-shaped ground signature that is propagated from the mixed-fidelity $A_e$ while retaining the practical aspects of the configuration. Initially, because of relatively large differences between the CFD $A_e$ and target $A_e$ of the baseline, the first mixed-fidelity iteration requires appreciable changes to the fuselage in order for the mixed-fidelity $A_e$ to effectively match the target $A_e$ and result in a shaped ground signature (see Fig. 4). At this point, a second CFD analysis is run, and the equivalent area from the CFD analysis is calculated. With CFD $A_e$ of the first mixed-fidelity design, only small changes to the fuselage are necessary to create a match between the mixed-fidelity $A_e$ and the target $A_e$ for $Xe \leq 130$; the ground signature of the reshaped design is considered to be slightly better (see Fig. 5) because the maximum overpressure of the ground

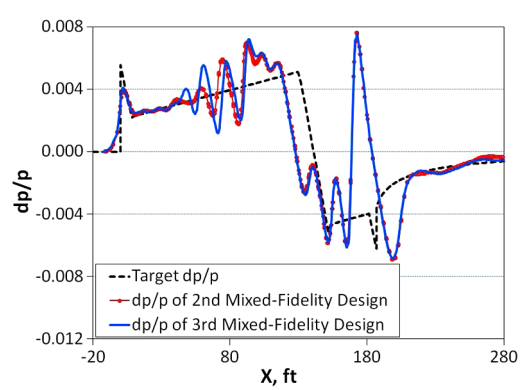


**Fig. 7 Comparison of $dp/p$ at $H/L = 3$.**

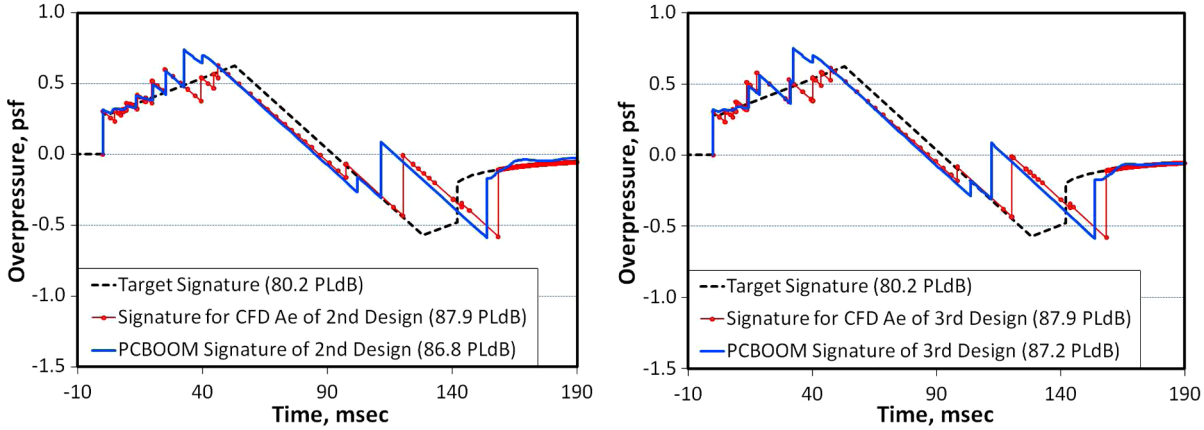


**Fig. 8 PCBOOM ground signatures propagated from $dp/p$ at $H/L = 3$.**

signature for CFD $A_e$ is reduced from 0.68 to 0.6 psf. The iterative process is necessary because the mixed-fidelity $A_e$ is only an approximation of the CFD $A_e$. The mixed-fidelity design process terminates when reshaping does not result in a better design (see the third iteration of the mixed-fidelity design in Fig. 6).

## IV. Verification of Mixed-Fidelity Low-Boom Design

The low-boom configurations that are designed by using $A_e$ analysis must be verified by analyzing the ground signatures that are propagated from the midfield pressure distributions. The USM3D solution with a stretched grid is used to generate a high-resolution midfield pressure distribution for the boom analysis. The pressure distribution at three body lengths below the configuration is used as input for the PCBOOM analysis. See Fig. 7 for the target $dp/p$ and $dp/p$ for the mixed-fidelity designs at three body lengths ($H/L = 3$ or 17 semispans) below the configuration.

The ground signatures for the second and third mixed-fidelity designs are shown in Fig. 8. Even though the signature that is propagated from CFD $A_e$ differs from the signature that is propagated from the midfield pressure distribution, both front shapes are similar to the ramp target signature and have similar perceived loudness values.

## V. Conclusions

A low-fidelity low-boom design process has been enhanced with the use of automated computational fluid dynamics (CFD) analysis. The resulting mixed-fidelity low-boom design process can be used to match the CFD $A_e$ of a configuration to a predetermined low-boom target $A_e$ with a few CFD aeroanalysis runs. A low-fidelity low-boom configuration was used as the baseline to demonstrate the mixed-fidelity design capability. The final mixed-fidelity designs were verified by propagation of offbody pressure distributions that were calculated by using USM3D with stretched grids. The CFD ground signatures of the mixed-fidelity designs differed slightly from the ground signatures that were propagated from the CFD $A_e$, but all of the signatures had front shapes that were similar to the ramp target signature. This study provides empirical evidence that CFD $A_e$ matching is a viable method for obtaining a configuration that is close to a low-boom design with CFD boom analysis.

The full cycle of low-boom design usually starts with low-fidelity $A_e$ matching, refines the low-fidelity design with CFD $A_e$ matching, and then tailors the offbody $dp/p$ for the final low-boom design. This paper shows a method for the second step in this design cycle. To make this method more effective, we will develop a tool to generate low-boom $A_e$ targets that can be matched by CFD $A_e$ of a configuration over the whole target range instead of the front part.

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