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Aeroacoustics of Propulsion Airframe Integration: Overview of NASA's Research

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ABSTRACT

The integration of propulsion and airframe is fundamental to the design of an aircraft system. Many considerations influence the integration, such as structural, aerodynamic, and maintenance factors. In regard to the acoustics of an aircraft, the integration can have significant effects on the net radiated noise. Whether an engine is mounted above a wing or below can have a significant effect on noise that reaches communities below because of shielding or reflection of engine noise. This is an obvious example of the acoustic effects of propulsion airframe installation. Another example could be the effect of the pylon on the development of the exhaust plume and on the resulting jet noise. In addition, for effective system noise reduction the impact that installation has on noise reduction devices developed on isolated components must be understood. In the future, a focus on the aerodynamic and acoustic interaction effects of installation, propulsion airframe aeroacoustics, will become more important as noise reduction targets become more difficult to achieve. In addition to continued fundamental component reduction efforts, a system level approach that includes propulsion airframe aeroacoustics will be required in order to achieve the 20 dB of perceived noise reduction envisioned by the long-range NASA goals. This emphasis on the aeroacoustics of propulsion airframe integration is a new part of NASA's noise research. The following paper will review current efforts and highlight technical challenges and approaches.

1. INTRODUCTION

NASA has a long history of aircraft noise research dating back to at least the 1960's. This research has been done with significant contributions from a wide variety of industrial partners and universities. One of the best summaries of aircraft noise research covering developments up to 1991 was edited by Hubbard.[1]

In recent years, NASA conducted the noise reduction element of the Advanced Subsonic Transport (AST) program from 1994 to its conclusion in 2001. This program produced development of such technology as the scarf inlet, chevron nozzles, swept and leaned stators and advanced liner treatment. This technology was also demonstrated at large-scale including full-scale engine tests. The AST program met its minimum success goal of demonstrating 8 dB of noise reduction over 1992 technology. Recently, as part of their own research and development, Boeing and Rolls-Royce demonstrated many of these technologies in a flight test on board a Boeing 777-200ER with Rolls-Royce Trent 800 engines.[2]

Immediately following the AST program, NASA launched the Quiet Aircraft Technology program with the aim of developing noise reduction technology for an additional 5 dB to be demonstrated at the laboratory environment. Prior experience has shown that for any newly identified noise source it is relatively easy to achieve the first few decibels of noise reduction by conventional means. To achieve subsequent reductions in noise levels, however, a significantly higher level of innovation and resulting research and development is necessary. The success of the AST program has largely brought the community to this level.

The QAT program also has a long-range goal of identifying and beginning the development of noise reduction technology that will enable 20 dB of perceived noise reduction. Such dramatic reduction is anticipated to be necessary in order to enable the growth of the commercial air transport system by meeting the continued demands of the traveling public and surrounding communities.

The QAT program has included new elements in order to meet the twin goals of achieving increasingly difficult noise reduction on conventional configurations and to begin to identify and develop technology for revolutionary noise reduction. Research efforts continue on noise reduction for the key noise source components. Recently, Envia reviewed fan noise research[3] and Kinzie and Bridges reviewed on-going jet noise research[4]. But in addition to component research, NASA has added new sub-projects to the QAT program including one to address the aeroacoustic effects of installation, or Propulsion Airframe Aeroacoustics (PAA).

2. PROPULSION AIRFRAME AEROACOUSTICS

In the past, there has been no focused research effort at NASA on the aeroacoustic effects of propulsion airframe installation. As such PAA represents a new area of opportunity to develop noise reduction technology for conventional configurations. This opportunity includes both reducing the noise sources that arise specifically from integration of propulsion and airframe and also using the installation itself as a means to reduce noise of a particular airframe or propulsion source. And with a longer range horizon, PAA represents a key opportunity to develop technology that will enable the 20 dB noise reduction goal by researching the effects of revolutionary aircraft configurations.

In general, the aeroacoustic issues related to propulsion airframe integration (PAA effects) are many and can be grouped in various ways. Fundamental PAA effects can be grouped into those issues having to do with flow interaction and those having to do with acoustic propagation although these are not entirely unrelated issues. Flow interaction effects are caused by the flow field of one component interacting with another specifically because of the location or orientation of installation. An example of this is the influence of the engine mounting pylon on the core jet exhaust flow. The influence of the pylon creates flow features in the jet that are not present in an isolated jet. These features are then also influenced by aircraft angle of attack. Another example is the possible interaction of the fan or core jet exhaust flow with an extended flap and its flow particularly for the typical engine-under-the-wing configuration. These types of flow interaction effects from installation can create new acoustic sources or they can modify existing acoustic sources already associated with components.

Acoustic propagation effects arise when noise generated from various components propagates and interacts either with structure or with flow features created by flow over the airframe and propulsion device. The acoustic propagation of fan noise along the exhaust duct, for example, is altered by the presence of the bifurcator and pylon. Furthermore, the fan noise propagation can be scattered off deployed flaps compared to propagation of fan noise in isolation. Reflection of jet noise off of the underside of the wing for the typical engine-under-wing configuration is another example. Acoustic propagation effects are unlikely to create new noise sources specifically due to installation effects however, these effects can conceivably modify existing component noise sources. An example of this modification could be the reflected jet noise interacting with the jet noise sources.

Another useful method of classifying PAA effects is along functional lines beginning with “conventional” and “revolutionary” aircraft configurations. Conventional PAA deals with the effects relevant to the two typical conventional configurations, tail mount and engine-under-the-wing. Some major effects include reflection and scattering of radiated noise off the wing and fuselage and high-lift surfaces; installed jet noise effects such as the jet-pylon interaction and effects of the pylon on jet noise devices such as chevrons; jet-flap interaction effects when high-lift surfaces are deflected; and forward radiated fan noise scattering off of the fuselage.

PAA effects on revolutionary aircraft that are different from those mentioned above will be dependent on specific unconventional propulsion airframe technology used. However, it is likely that major effects will be included from acoustic propagation such as reflection, scattering, and shielding of propulsion noise sources by the airframe and flow interaction effects stemming from highly integrated configurations such as exhaust distributed over large portions of the wing.

NASA’s PAA sub-project has been organized along lines reflecting the classifications discussed above. A significant portion of the program focuses on conventional configurations while a fraction of the program is concentrating on revolutionary PAA technology and configurations. Another segment of the program develops physics based prediction methods primarily targeted at conventional configurations but that will also be useful in analyzing revolutionary configurations. The remainder of this paper discusses highlights of these areas of the PAA sub-project.

3. CONVENTIONAL PROPULSION AIRFRAME AEROACOUSTICS

Jet noise from a conventional engine-under-the-wing configuration can have installation effects from the pylon, wing downwash, and jet-flap interaction but there can also be installation effects on jet noise reduction devices installed on the jet. Chevron nozzles are an example of a jet noise reduction device that has been studied extensively for isolated jets in recent years.[5] One area of research in the PAA sub-project has been toward understanding these effects on installed jet noise including the effects of installation on chevron noise reduction devices. This includes a coordinated effort between computational analysis of the flow field, acoustic experiments, measurements of the flow field properties, and an installed jet noise prediction method development.

As a part of this coordinated effort, computational studies have been reported for bypass ratio (mass flow of fan flow to mass flow of core flow) five separate flow nozzles including cases with pylon and chevrons.[6] RANS CFD was performed for five configurations including a baseline bypass ratio five separate flow nozzle, a baseline nozzle with pylon, an eight-chevron core nozzle, and the eight-chevron core nozzle with pylon. All nozzles had the same baseline fan nozzle. Figure 1 shows the computation grid, close to the nozzle, of the case with pylon and eight-chevron core nozzle. The RANS solutions document the flow fields very well. Details of the interactions between jet and pylon are clearly seen in various flow quantities such as total temperature and turbulent kinetic energy. The effect of the pylon is to distort both the core and the fan jet with the largest effect being on the core jet. Figure 2 shows contours of total temperature on the symmetry plane of the baseline jet and then the baseline with a pylon. The pylon also affects the chevron jet flow field by distorting the chevron lobes around the whole circumference. The orientation of chevrons relative to the pylon was found to have a significant effect on the development of the lobes in closest proximity to the pylon.

The computational results were used in designing some of the details of the configurations used in subsequent experiments. The computational solution is also used as a basis for the jet noise prediction method under development. The jet noise prediction theory is based on the Lighthill Acoustic Analogy and it has been implemented into the computational code JET3D.[7] Implementation of the Lighthill theory in JET3D centers on the modeling of two-point space-time correlations. Mean flow correlations for velocity and density are modeled using a Taylor series expansion, written in terms of local mean flow gradients. Turbulent velocity correlations are separated into space and time factors, and modeled using a combination of Gaussian-type exponential functions and quadratic functions. Basic validation of the JET3D code has been accomplished on a supersonic jet and work is progressing toward using the JET3D code on complex three-dimensional subsonic jets beginning with the separate flow nozzles including pylon and chevron nozzles.

In addition, experiments on these same configurations have been performed at the Jet Noise Laboratory of the NASA Langley Research Center (see Figure 3). These experiments have measured the mean flow quantities of pressure and temperature and in separate experiments the acoustic directivity. These results are being used to validate the CFD of the mean flow field and the installed jet noise prediction capability of the JET3D code.[8,9] Together, this coordinated approach is leading toward a set of CFD and noise prediction tools for complex installed jet cases which will then be used to investigate noise reduction concepts.

4. PREDICTION METHODS FOR CONVENTIONAL CONFIGURATIONS

Empirically based prediction methods have been used extensively in the aeroacoustics community and work well within their inherent limitations. However, the need to predict the effects of design variations without expensive hardware and tests and the need to research increasingly unconventional noise reduction technology together with increasing computational resources combine to shift the focus toward the development of more physics based prediction methods. The development of installed jet noise prediction methods such as JET3D mentioned above is one physics based method under development in the PAA sub-project.

Another area of method development involves the prediction of acoustic scattering of engine generated noise by the aircraft configuration. Acoustic scattering can have significant effects for conventional configurations such as reflection of jet noise off the wing or of fan noise off the fuselage. These effects can impact the net noise radiated to the community below and are, therefore, increasingly important to be able to predict accurately and incorporate into system noise prediction methods. It is also expected that these methods will be important in exploring the design of unconventional aircraft configurations that are aimed at producing perceived noise reductions on the order of 20 dB. This is because such noise reduction will likely be obtained with aircraft configurations that take advantage of shielding of engine noise by aircraft configuration itself.

The PAA sub-project has a range of these methods under development. The method that has progressed the most involves the spectral element method.[10] In a recent report both the time domain and the frequency domain versions of the code are used to compute the noise radiated from an engine for a tail mounted aircraft configuration.[11] Figure 4 shows the acoustic pressure contours computed with the time domain method on the surface of the aircraft at the non-dimensional time of T=44 for the propagation of mode (18,0). The computation is done for the case with no flow over the aircraft. When compared to the sound pressure level on the wing, the computed results show correct trends. Further improvements are expected when the effect of the flow over the aircraft is included in the computation. These computations are large calculations, this one requiring 10 days on a 32-processor node (1.1 GHz) of an IBM SP4 machine.[11]

5. REVOLUTIONARY PROPULSION AIRFRAME AEROACOUSTICS TECHNOLOGY

To meet NASA's long-range goal of 20 dB of perceived noise reduction, revolutionary technology and aircraft configurations will be required. One technology that is being investigated is the distributed exhaust nozzle (DEN). The DEN concept is being pursued because of the significant jet noise reduction potential together with the idea that the distributed exhaust concept lends itself to being integrated into a revolutionary airframe. Noise reduction from the DEN results from a favorable shift in the spectral shape of the radiated jet noise. The smaller jets of the distributed exhaust radiate noise at higher frequency than an equivalent round jet. Atmospheric attenuation increases nearly exponentially with increasing frequency providing a powerful factor for additional reduction of noise radiated to the ground from DEN concepts. In addition, the high frequencies (above 10 KHz) do not even contribute to the EPNL calculation. Also, depending on how the small DEN jets are arranged relative to the ambient flow, mixing can be increased significantly reducing jet velocities and temperatures rapidly impacting favorably the low frequency noise and the infrared signature. Against these strengths of the DEN concept are the disadvantages of a thrust penalty of about 5% and the potential weight increase of a DEN compared to a round reference nozzle.

NASA has been working with the Northrop Grumman Corporation on the DEN concept in the PAA sub-project. Computational tools for design, performance assessment, and noise estimation have been under development. Also, several DEN concepts have been built and tested at NASA Langley. Recent nozzles that have been built and tested include a nozzle of many small round nozzles called a drops nozzle, Figure 5, and a nozzle of slanted pseudo-slots, Figure 6. Both nozzles have demonstrated up to 20 dB of noise reduction on a spectral basis and up to 10 dB on an overall basis relative to the round reference nozzle as can be seen in Figure 7 for the drops nozzle and Figure 8 for the pseudo-slot.[12] Both DEN nozzles and the reference nozzle were operating at a nozzle pressure ratio (NPR) of 1.72.

6. SUMMARY AND FUTURE DIRECTIONS

In recent years, NASA has included in its Quiet Aircraft Technology program a sub-project to research and develop noise reduction technology based on the aeroacoustics of propulsion airframe integration. Research is being conducted in the areas of conventional configuration propulsion airframe integration, physics based modeling and revolutionary propulsion airframe integration technology. For conventional configurations the research is focused on identifying and quantifying the aeroacoustic effects that can be identifying specifically with propulsion installation. The physics based modeling research includes developing the methods to predict the effects of installed jet noise from complex geometries as well as to predict the scattering of engine generated noise from the airframe. Distributed exhaust nozzle concept is being developed as an example of technology that could revolutionize the integration of propulsion and airframe and, therefore, the aircraft configuration. Together with the rest of the Quiet Aircraft Technology program these developments in the aeroacoustics of propulsion airframe integration are making progress toward quieter aircraft technology.

7. REFERENCES

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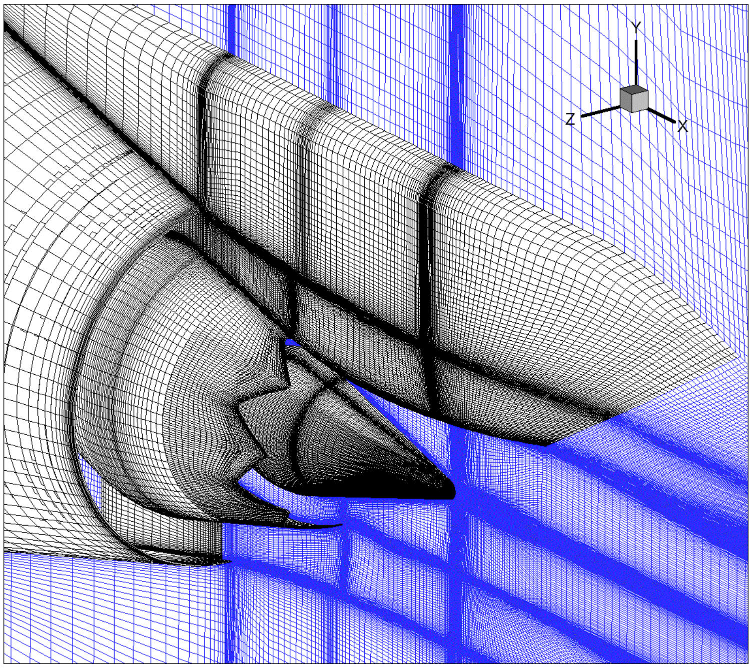


Figure 1. Computational grid of separate flow nozzle with pylon and core chevron nozzle. From Reference 6.

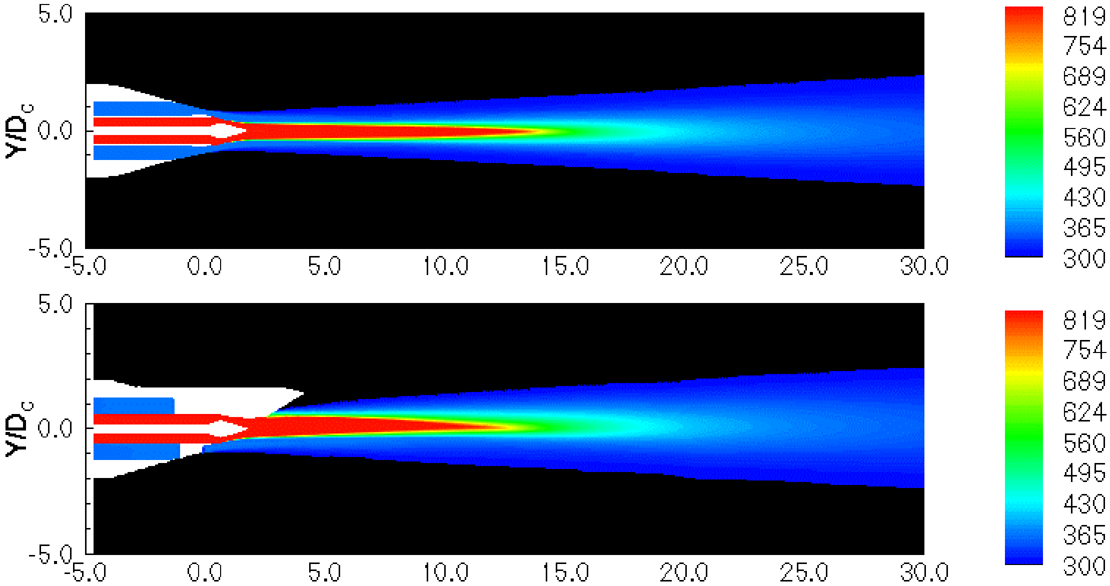


Figure 2. Total temperature (degrees K) contours in the symmetry plane of the baseline bypass ratio five nozzle (top, nozzle in white) and the baseline nozzle with pylon attached (below). Flow from left to right. From Reference 6.

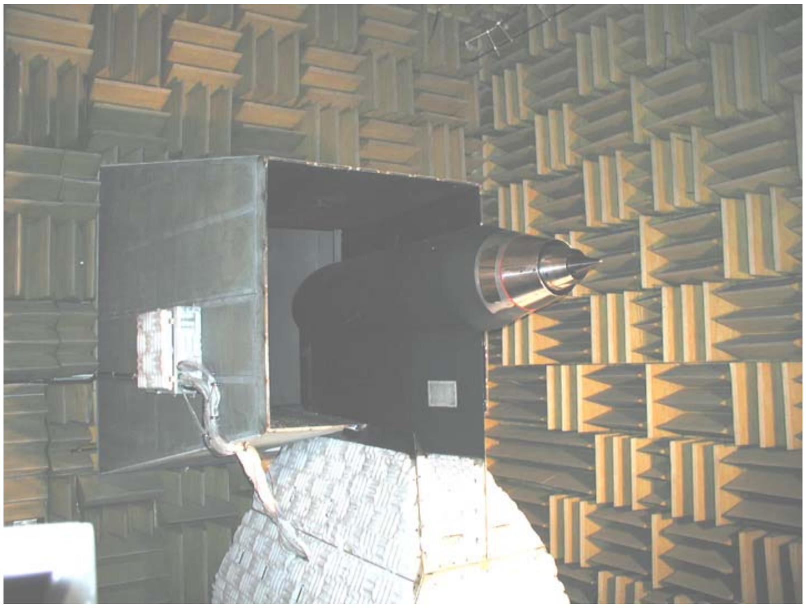


Figure 3. Baseline bypass ratio five separate flow nozzle installed on the jet engine simulator in the test cell of the NASA Langley Low Speed Aeroacoustics Wind Tunnel.

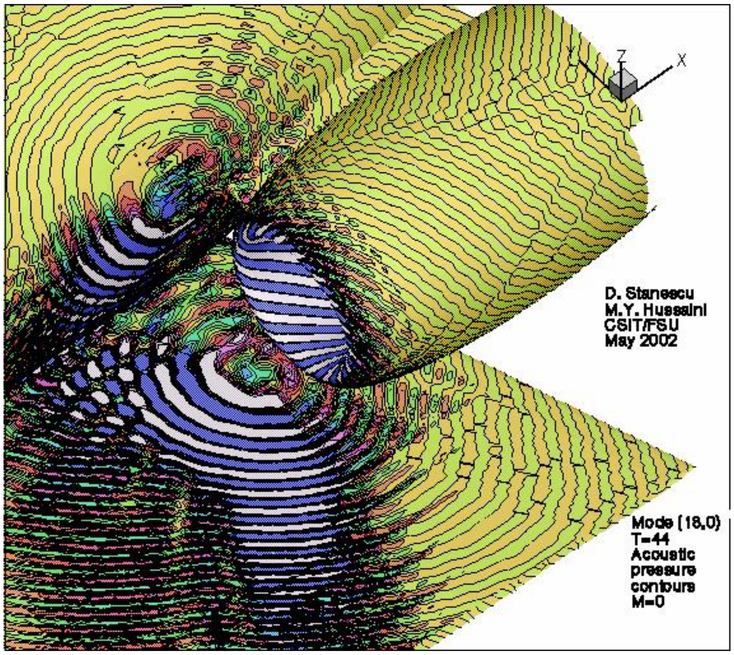


Figure 4. Snapshot at nondimensionalized time of T=44 of the acoustic pressure contours on the surface of the fuselage, nacelle, and wing of a tail mounted aircraft configuration. The acoustic radiation is generated by a 18,0 mode with no background mean flow. From Reference 11.

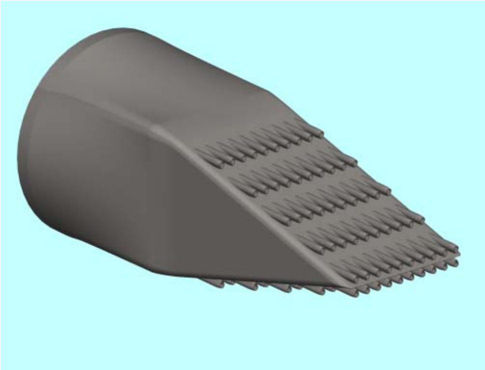


Figure 5. Model of the drops distributed exhaust nozzle. From Reference 12.

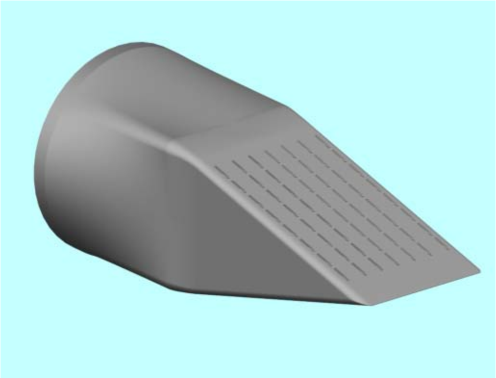
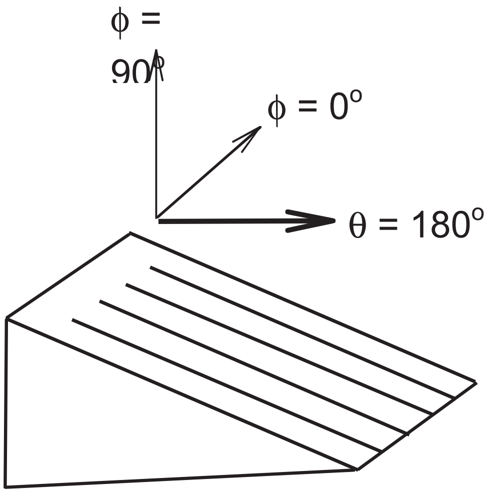


Figure 6. Model of the pseudo slot distributed exhaust nozzle. From Reference 12.



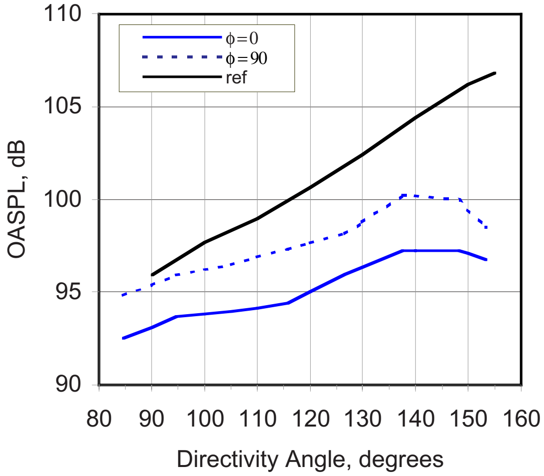


Figure 7. Overall sound pressure in decibels as a function of directivity angle, θ (180 is the flow direction), for the drops nozzle. Angle ϕ refers to the orientation of the nozzle with respect to the microphones. From Reference 12.

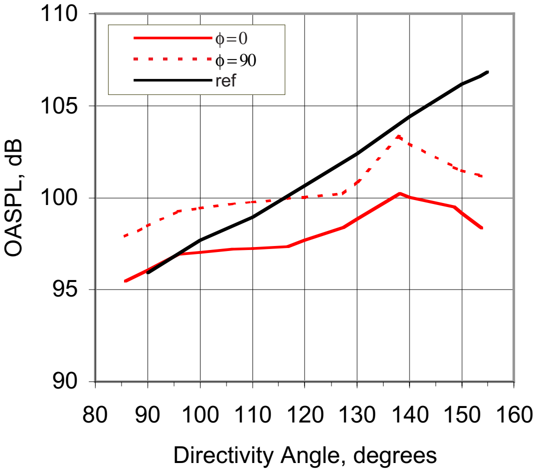


Figure 8. Overall sound pressure in decibels as a function of directivity angle, θ (180 is the flow direction), for the pseudo slot nozzle. Angle ϕ refers to the orientation of the nozzle with respect to the microphones. From Reference 12.