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APR / MAY ‘24

VOL. 63 NO. 2

GLOBAL GAS TURBINE NEWS

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AMERICAN SOCIETY OF MECHANICAL ENGINEERS (ASME)

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C-17 Globemaster Jet Engine Thrust Reversers

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The ever-adaptable jet engine not only provides forward thrust for aircraft flight, but it can be configured to provide reverse thrust. This reversal can augment the safe braking of both commercial and military aircraft during landing.

Gas turbine or jet engine thrust power is equal to the momentum increase in the mass flow from engine inlet to exit, multiplied by the flight velocity. The actual thrust force produced in the engine (and pulling the plane forward) is the summation of all the axial components of the pressure and frictional forces generated by the gas path flow on stators and struts attached to the engine case. Case engine mounts then transmit the thrust forces to the wing pylon (for a wing-mounted jet engine) to pull the aircraft forward.

A jet engine thrust reverser is a device mounted in the engine nacelle to divert some portion of engine flow in a forward direction to flight, using the momentum of the reversed flow to slow the aircraft. It is activated by the pilot or the aircraft flight control system on landing. (An attentive passenger can detect its deployment by a sudden high- pitched increase in engine noise, just after touchdown.) The thrust reverser deployment alters engine thrust forces reviewed in the last paragraph, so that the wing pylon now pulls back on the aircraft's forward motion.

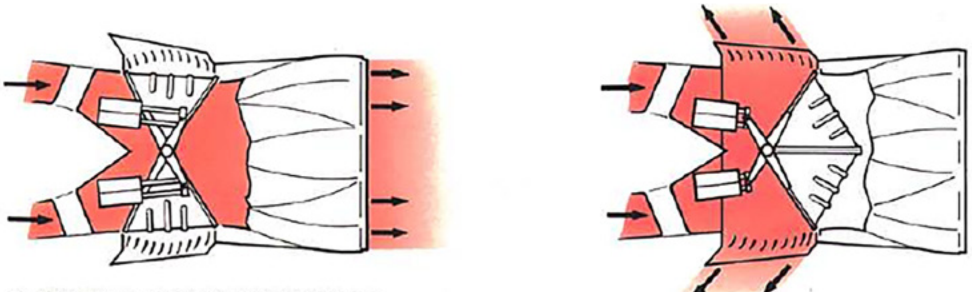
There are a variety of thrust reverser designs, for both turbojets and turbofan engines. I refer the reader to engine OEM publications, such as one by Rolls-Royce[1], for more details.

C-17 THRUST REVERSERS PROVIDE UNIQUE VERSATILITY

The deployment of thrust reversers on the U.S. Air Force's McDonnell Douglas/Boeing four-engine C-17 Globemaster is an example of the unique versatility they can offer to aircraft operation.

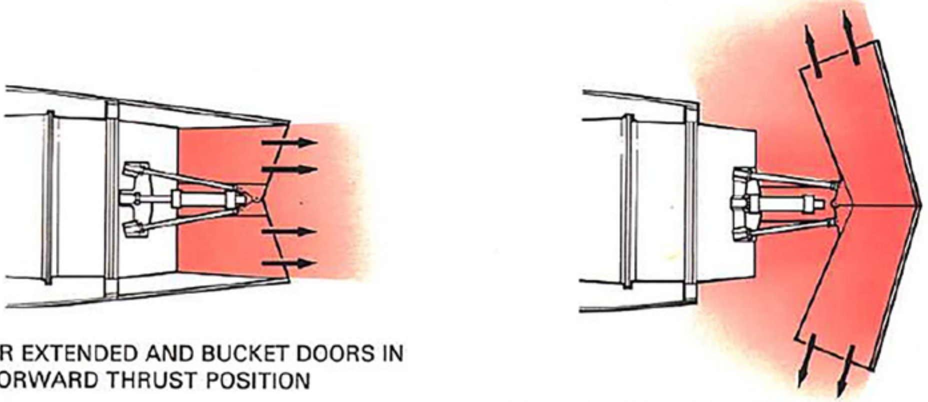
The C-17 Globemaster III (shown in Fig.1) is typically

Figure 1. McDonnell Douglas/ Boeing four engine C-17 Globemaster III in flight.



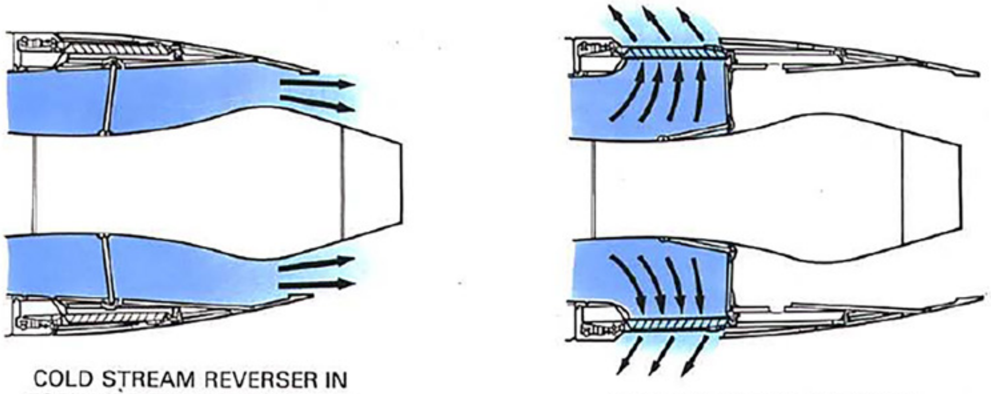
CLAMSHELL DOORS IN FORWARD THRUST POSITION

CLAMSHELL DOORS IN REVERSE THRUST POSITION



ACTUATOR EXTENDED AND BUCKET DOORS IN FORWARD THRUST POSITION

ACTUATOR AND BUCKET DOORS IN REVERSE THRUST POSITION



COLD STREAM REVERSER IN FORWARD THRUST POSITION

COLD STREAM REVERSER IN REVERSE THRUST POSITION

Figure 2. Various thrust reverser designs. The simplified schematic showing the cold stream class is used in C-17 nacelles. (1)

flown by a crew of three and is perhaps the most flexible military cargo aircraft in the world. At a maximum payload capacity of 170,900 pounds, it can carry a 70-ton Abrams tank to a battlefield or, as on August 15, 2021, the US Air Force transported 823 Afghanistan citizens from Kabul in a single flight during a humanitarian mission.

The 174-foot-long C-17 is powered by four Pratt & Whitney F117 turbofan engines, each rated at 40,400 pounds thrust and mounted in nacelles under the high-lift, swept-back 170-foot span wing for maximum ground clearance. C-17 cruise speed is 450 knots (0.74 Mach number) with an unrefueled range of about 2400-2800 nautical miles, depending on which model[2]. A takeoff distance at maximum weight is 8,200 feet.

Designed and built by McDonnell Douglas at their DC-10 plant, the first C-17 flew in Long Beach, California on September 15, 1991. Later, in 1997 the company merged with Seattle's Boeing, with C-17 production continuing in Long Beach, until the last delivery in 2013. In all 279 C-17's were produced, with 223 going to the US Air Force (giving it a monstrous single nation lifting capacity) and the remaining 56 to other national militaries.

The C-17 thrust reversers (identified in Fig. 2 as a cold stream reverser (of fan flow)) are of a unique and flexible design, providing an exit area for reverse flow for only half of their full circular circumference (see Fig. 3). The reverse flow is directed upward and forward, to avoid dust and debris production when landing on an unimproved (austere) field. This reduces the risk of possible debris ingestion, which could damage the F117 engines[4]. (In [4], the video (with sound) shows the C-17 landing with thrust reversers activated (detected by the higher-pitched revved-up engine noise), with no sign of stirred-up ground debris being ingested by the engines.)

With the thrust reversers, the C-17 can operate on unpaved, unimproved runways as short as 3500 feet, and as narrow as 90 feet. On the ground the thrust reversers can back a fully loaded C-17 up a two-degree slope. In flight, the C-17 thrust reversers can be deployed, to provide a rapid aircraft descent.

A C-17 THRUST REVERSER DEVELOPMENT COLLABORATION VIGNETTE

Since the C-17 thrust reverser only provided exit area for the Pratt & Whitney F117 fan flow over about half of the circumference, there was a concern for non-uniform back pressure that would reduce the fan stall margin.

In 1990, my P&W colleague, Senior Fellow and engine stability expert Bob Mazzaway[3] had, evaluated this threat and showed analytically that axial spacing from the fan was sufficient to prevent a problem. Naturally, the Air Force needed a proof test which was scheduled to take place at the P&W test facilities in Florida using the first McDonnell Douglas nacelle.

By sheer luck, my colleague, Senior Fellow and aeroengine expert Pentti Nikkanen walked past the engine with the McDonnell Douglas nacelle on the East Hartford assembly floor, as it was being prepped for shipment to Florida. He noticed that the reverser cascades (see Figures 2 and 3) were missing axial "strongbacks", a structural component that reinforces the thin, high aspect ratio airfoils of the cascade. This prompted an emergency telecon with McDonnell Douglas to alert them. At one point they sent an engineer to inspect the thrust reverser on their DC-10 aircraft nacelle designed by GE. He reported back to the meeting confirming "strongbacks" in that installation. Since the proof-of-concept test was vital to the program, it was decided to wire lace the cascade airfoils to reinforce them. The Air Force was also alerted to the issue. The reinforced cascades lasted long enough to confirm the fan stability predicted by Mazzawy. Testing ended shortly thereafter with the cascades "leaving the premises" .... the wire lacing endured just long enough, having saved the day for both companies. ◆

Figure 3. C-17 wing mounted F117 nacelle with thrust reverser deployed, showing cascades for providing reverse flow on upper half of the nacelle only.

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Challenges of Boundary Layer Ingestion Engine Design and Future Directions

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As aircraft designs continue to mature, it becomes increasingly challenging to develop new concepts that can provide significant improvements relative to existing systems. New designs must incorporate more highly integrated subsystems in order to exploit opportunities for improvements. A key goal of next-generation propulsion systems is to provide continued reductions in fuel burn not only relative to current technology, but also in comparison to the vision for gas turbine engines currently in development. One new technology currently receiving considerable attention is boundary layer ingesting (BLI) propulsion systems. Boundary layer ingestion can provide substantial propulsive efficiency improvements relative to clean-inflow systems by producing thrust using the reduced velocity air in the incoming boundary layer. The low-momentum boundary layer fluid is ingested into the engine and subsequently exhausted into the wake of the aircraft. However, in order to realize system-level benefits, the propulsion system must be capable of performing well in a high-distortion environment. The position of the engine in future aircraft determines the amount of the boundary layer that must be ingested and thereby the benefit obtained.

An estimate of the propulsive efficiency (η_p) for an installed system can be written as:

$$\eta_p = \frac{2V_0}{\left(V_j + V_{in}\right)}$$

where V_0 is the freestream velocity, V_j is the jet velocity, and V_{in} is the inlet velocity. Figure 1 shows the conventional propulsion system as compared to one of the BLI configuration.

An alternative description of the BLI benefit can be presented in terms of wake filling, and the associated reduced dissipation in the aircraft wake as shown by Drela[1]. The limiting factor in the degree to which BLI benefits can be realized is how much of the aircraft boundary layer can actually be ingested into the engines. A simple theory of the maximum theoretical BLI benefit can be estimated using a simple theory formulated by Smith[2].

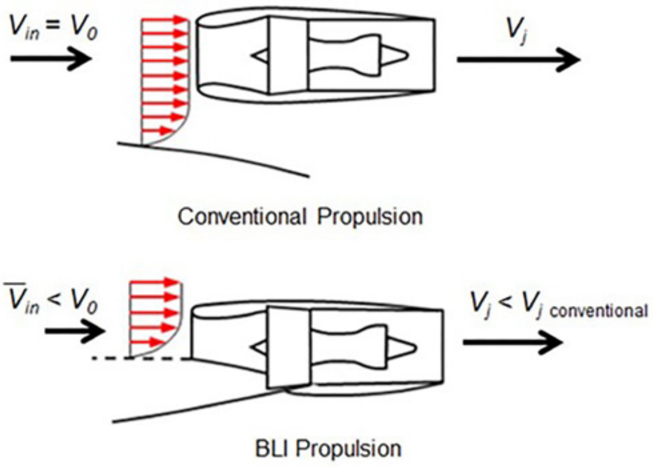

Figure 1. Comparison of the velocity streams for a conventional and BLI engine configuration.

Figure 2 shows several aircraft formulations that have been considered for obtaining the benefits of BLI installations. With these BLI installations, the performance of the aircraft and the performance of the propulsion system can no longer be considered separately. The normal bookkeeping of ram drag, inlet pressure recovery, cycle efficiency, and thrust production must be considered, just as in wing-mounted engines, but in addition, the associated aircraft performance must be captured with parameters such as weight, airframe drag, nacelle drag, and interference drag associated with the propulsion system installation. With BLI installations, the airframe and propulsion systems are more highly coupled since the propulsion system inflow no longer comes from clean freestream flow, but rather from a highly-distorted inlet flow that the propulsion system must be able to handle. Of the formulations shown in Figure 2, significant work has been performed on the N2A-EXTE Hybrid Wing Body Aircraft BLI configuration by United Technologies Research Center and NASA.

Because the engines cover only a limited portion of the vehicle, only a portion of the overall airframe drag (and boundary layer) can be ingested. Therefore, the BLI benefit is highly configuration-dependent and is a strong function of the amount of boundary layer entering the engine inlets. In work by

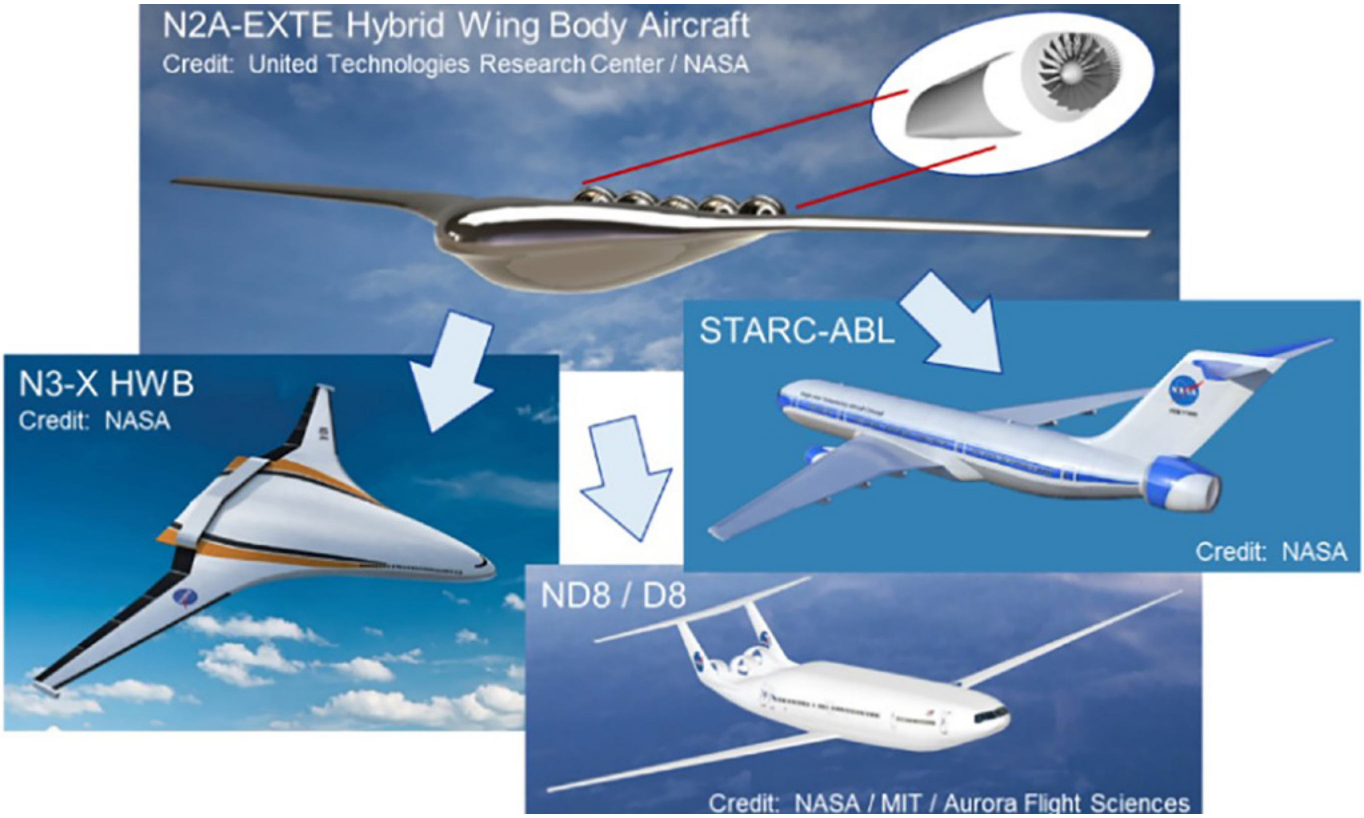

Figure 2. Several recent aircraft considered for BLI configurations.

Tillman, et.al.[3], it was shown that ingesting ~15% of the airframe drag results in a propulsive efficiency benefit on the order of 5%.

For the N2A-EXTE Hybrid Wing Body Aircraft, extensive studies were performed on the configuration and it was found that the fuel burn benefit for the configuration shown in the figure would be about 4.5%. The work performed on this airframe BLI configuration spanned a 10-year period, and included detailed airframe studies, a serpentine inlet design (since the engine is embedded), an integrated design of the inlet and a single-stage fan, and finally a test series performed in the 8 ft. x 6 ft. wind tunnel at NASA Glenn. The wind tunnel was modified with a false floor and a system to generate the proper simulated aircraft boundary layer at 0.8 Mach number. This is a significant achievement as the program is the only one to date that performed such a complete design, manufacture, and test of this difficult BLI configuration.

The challenges associated with BLI aircraft/propulsion system integration are many, and require new thinking with regard to the analysis and integration of the associated systems. It must be recognized that there are penalties to boundary-layer-ingesting propulsion. These impacts need to be managed in both the cycle definition and the propulsion system design. Increased inlet duct losses resulting from highly-airframe-integrated inlet geometries increase the total pressure loss at the engine face, directly impacting engine performance. In addition, such inlet configurations combined with the effect of boundary layer ingestion result in significantly increased total pressure and swirl distortion at the engine face. This distortion can have an adverse impact on the fan efficiency, and can propagate downstream into other portions of the engine such as the low-pressure and high-pressure compressors. Resulting losses in stability margin for both the fan and the compressor can adversely impact the efficiency of these components. Recovering lost stability margin may require operating at non-peak-efficiency conditions. Finally, while bypass ratio (BPR) is not directly affected by boundary layer ingestion, it should be noted that distortion can have a larger effect on higher-efficiency, high bypass ratio engines that operate at lower fan pressure ratio (FPR). As BPR increases, the thrust is produced by accelerating more air to a lower jet velocity as compared to a lower BPR engine. This process is accomplished with reduced fan pressure ratio. As FPR is reduced in the presence of a fixed-amplitude pressure fluctuation within a distorted inflow, there will be a point at which the pressure ratio will no longer be sufficient to pump the local unsteady distorted flow through the fan. Thus, if the unsteady fluctuating content of the distorted inflow is severe enough to force the move to a lower bypass ratio cycle in order to implement a BLI system, overall engine efficiency will be reduced relative to a higher-efficiency, non-BLI baseline. This is a key point, since any BLI system must deliver a net benefit relative to a high-performance, high-bypass-ratio, turbofan propulsion system mounted on the wing of the aircraft. The resulting challenge associated with boundary layer ingesting propulsion systems is therefore the ability of the turbomachinery to operate efficiently in the highly-distorted flow, thereby preserving the BLI system-level benefits as well as meeting aeromechanics-related operating requirements.

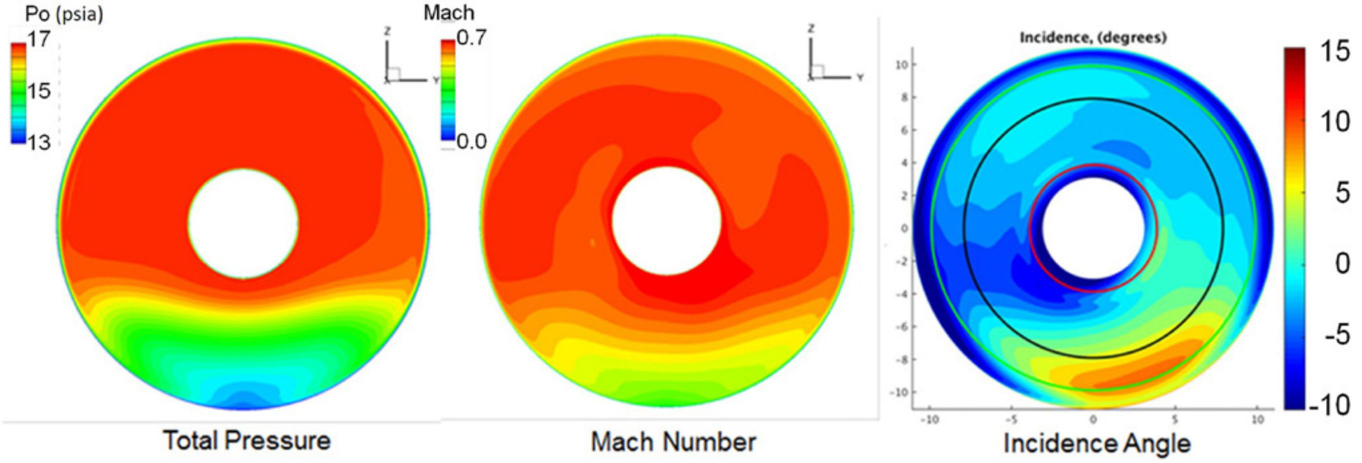

Figure 2. AIP distortion characteristics. Total pressure (left), Mach number (middle) and Incidence angle (right). Maximum of distortion: ΔPcirc/P ~ 10%, ΔPrad/P ~ 4%, Extent ~ 125°

To quantify some of these requirements, the integrated inlet/fan design in the program for the N2A-EXTE Hybrid Wing Body Aircraft had to meet severe aerodynamic and mechanical requirements. Figure 3 shows the flow characteristics at the aerodynamic interface plane (AIP) for the fan. With a circumferential total pressure distortion intensity (ΔPcirc/P) of 10% (where 6% is generally considered a high value), a radial total pressure distortion intensity (ΔPrad/P) of 4%, and an incidence variation due to swirl of about 17 degrees circumferentially, the fan aerodynamic response was designed to operate stalled in a small sector while still providing good overall performance. While managing the high inlet swirl, shaping of the blade was unique, since stringent mechanical design criteria had to be met for this configuration. Reference[4] discusses the fan design details and Reference[5] provides information on the very successful test program. While the N2A-EXTE aircraft system was the most challenging configuration for propulsion system integration and design, this particular program showed that BLI aircraft of many designs are indeed a possibility and that the future holds promise for more BLI configurations. ◆

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Boundary Layer Ingestion Aeroacoustics Challenges and Ongoing Research Efforts in Europe

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INTRODUCTION

Boundary layer ingestion (BLI) is a non-conventional propulsor aircraft integration technique in which the propulsor is installed closer to the airframe (Figure 1) to exploit the low momentum boundary layer or wake to increase its overall propulsive efficiency, e.g.[1,2]. However, BLI systems are also a cause of concern due to the potential increase in noise emissions with respect to conventional propulsive designs. In fact, the positioning of a propeller or turbo-fan engine within a turbulent inflow leads to complex interactions between the rotor blades and the turbulent eddies in the incoming flow, enhancing certain aerodynamic noise generation mechanisms.

Though BLI design solutions vary widely, a shared effect is the distortion of the incoming turbulent flow due to the boundary layer or the wake. This can be enhanced due to the acceleration imposed on the fluid by the propulsor. Specifically, such distortion consists in the elongation of turbulent structures in the streamwise direction, which can then in turn be ‘chopped’ multiple times at the blade passing frequency (BPF) of the rotor. This periodic ‘chopping’ of the same eddy leads to a coherent unsteady loading of consecutive blades, i.e., similar surface pressure fluctuations are experienced by subsequent blades at the location of the elongated vortical structure during their rotational motion around the rotor’s axis. Acoustically, unsteady forces acting on solid surfaces translate into pressure disturbances radiating to the surrounding fluid at the speed of sound, i.e. sound waves. While turbulent pressure fluctuations are distributed over a broad frequency range, the periodic intermittency of the ‘chopping’ process effectively amounts to a filtering of the incoming broadband field, as only structures with frequencies close to the BPF and its harmonics are allowed to interact constructively with the blades’ surfaces. For this reason, the typical noise emissions of BLI systems show a redistribution of the broadband noise component around the BPF and its higher harmonics in a phenomenon known as ‘haystacking’ due to the particular shape of the acoustic spectra. This further exacerbates the tonal nature of rotor-generated sound, a problem inherent to such technology. As an example, Figure 2 depicts three different power spectral density (PSD) far-field noise spectra emitted by a propeller partly immersed in a turbulent boundary layer. By placing the propeller in different streamwise positions (P1, P2, and P3, respectively) the boundary layer thickness increases and, hence, the immersion ratios (IR , with the distance between the outer propeller blade tip and the solid surface), see Figure 2 right. The spectra for the positions P2 and P3 present the aforementioned ‘haystacking’ phenomenon.

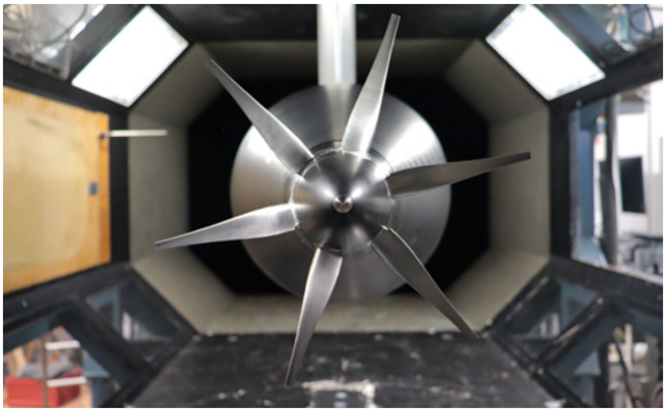

Figure 1. BLI-optimised model propeller installed at the aft of an axisymmetric body of revolution at the Low-Turbulence wind tunnel facility of Delft University of Technology (ongoing research within the Holland High-Tech and SAFRAN funded APPU project[3]).

Researchers have been investigating the issue of BLI noise since the 1970s, at first motivated by marine applications (where propellers are usually immersed in the ship’s hull boundary layer, e.g.[5]) and the ground effects of the atmospheric boundary layer during take-off conditions (where extremely elongated streamwise structures are ingested by the planes’

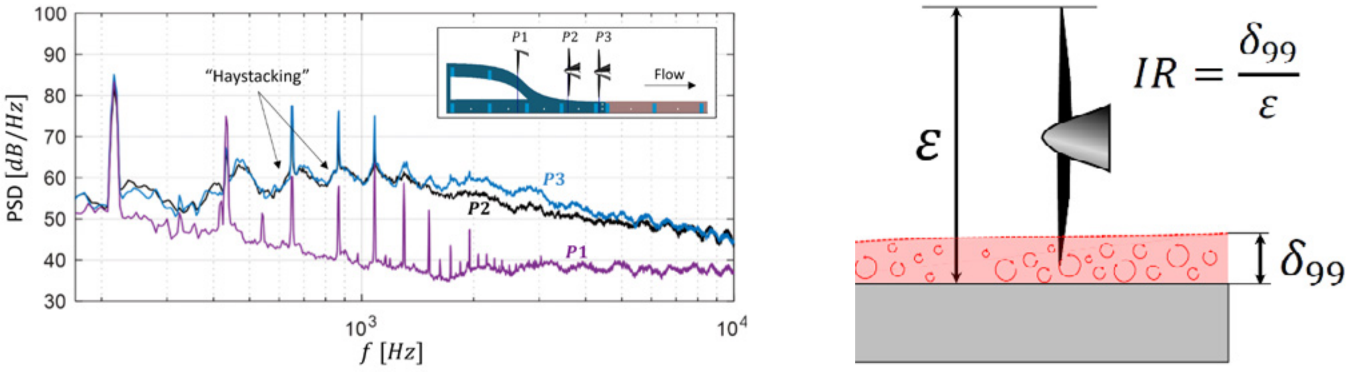

Figure 2. Evidence of 'haystacking' in the narrow-band power spectral density (PSD) of the far-field sound emitted by a propeller partly immersed in a turbulent boundary layer at different positions along an S-shaped step, adapted from Zaman et al.[4]. Right: Definition of immersion ratio (IR).

propellers, e.g.[6]). Interest has then been steadily increasing ever since, as both the benefits of BLI solutions in terms of fuel efficiency and the adverse health impacts of aircraft noise became apparent.

BLI RESEARCH IN EUROPE

Within the European context, recent works have been mainly experimental in nature. The case of an over-the-wing BLI propeller was investigated at a low-turbulence wind tunnel facility at Delft University of Technology by De Vries et al.[7], for which near-field surface pressure data over the wing were acquired for different immersion ratios. Zaman et al.[8] performed a similar study at the new aeroacoustics facility of the University of Bristol. During this campaign, far-field acoustic measurements confirmed the presence of 'haystacking' and its strong dependence on the IR (see Figure 2 right). At the same facility, the effects of inflow turbulence were also investigated on both open (or isolated) and shrouded propeller configurations using turbulence grids in the works of Jamaluddin et al.[9] and Go et al.[10]. By positioning several free-field microphones along the streamwise direction on an arc centered on the propeller's rotational axis at the propeller's plane, both studies investigated the directionality of the generated noise. For the isolated propeller case, it was reported that the overall sound pressure level (OASPL) at the BPF and its first harmonics follows a cardioid-like directivity pattern with maximum at the propeller's plane and minima in front and behind it, see Figure 3 left. The cases with increased levels of incoming turbulence intensity (denoted in Figure 3 as Grid A and Grid B) follow a similar pattern with slightly higher OASPL values. The high-frequency noise is instead dominated by the broadband component, especially for the cases with increased turbulence intensity, displaying maxima in front and behind the propeller's plane, see Figure 3 right.

On the other hand, the addition of a shroud around the propeller (not shown here) was seen to shift the OASPL minimum radiation direction at the BPF and its harmonics downstream of the propeller. Moreover, a slight increase of the broadband component was observed. Petricelli et al.[11], on the other hand, focused on investigating the acoustic effects caused by the non-homogeneity of inflow conditions in certain BLI installation configurations at the anechoic wind tunnel facility of the University of Southampton. By using non-uniform turbulence grids, varying degrees of inflow non-uniformity were achieved and effects on the tonality of noise emissions from the tested propellers were evaluated.

Confirming the growing interest in aircraft noise emissions amongst European research entities, the "DJINN-ENODISE conference" was held in Berlin on the days 22-24 November 2023 focusing on "aeroacoustic installation effects in conventional and new aircraft propulsion systems". The aim was

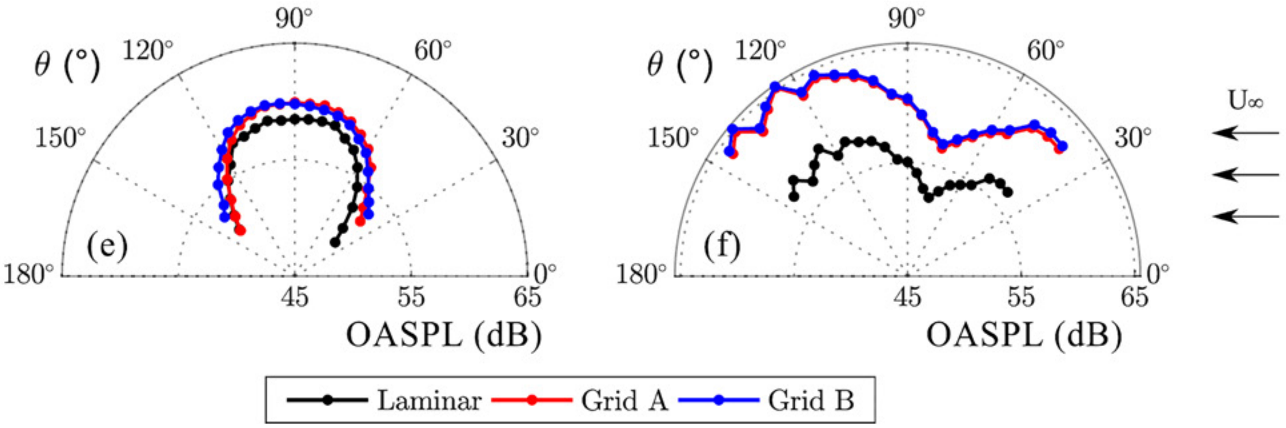

Figure 3. Polar plots of the overall sound pressure level (OASPL) at the first blade passing frequency (BPF, left) and of the broadband noise component (right) emitted by an isolated propeller subject to laminar and grid-turbulence inflows, from Jamaluddin et al.[9]

to share the results of the EU-funded projects DJINN (Decrease Jet INstallation Noise)[12] and ENODISE (ENabling Optimized DISruptivE airframe-propulsion integration concepts)[13] involving several European research centers. A number of the works presented specifically dealt with BLI systems. Klähn et al.[14] from the German Aerospace Center (DLR) showed how non-uniform inflows as those found in installed BLI configurations can be accurately reproduced in a test rig through variable-porosity flow conditioners. Zaman et al.[4] and Ahmed et al.[15] (University of Bristol) discussed the effect of an adverse pressure gradient boundary layer on the noise caused by both an isolated and a shrouded propeller.

A number of other European projects (e.g. APPU[3], and HOPE[16] at Delft University of Technology) testify to the ongoing efforts in the exploration of the aerodynamic and aeroacoustic characteristics of BLI systems. In particular, the APPU project is investigating experimentally the effect of the boundary layer thickness (and hence the immersion ratio, IR) on the performance and noise emissions of two different propellers mounted on the aft of a body of revolution representing a fuselage. The aim of the HOPE project, on the other hand, is to perform a fundamental characterization of the influence of the inflow conditions (e.g. turbulence intensity levels) and propeller operational conditions (e.g. blade pitch angle) on the noise levels generated. Based on those findings, the estimated community noise impact of an A320-like aircraft equipped with a BLI system at the aft of the fuselage will be investigated. ◆

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NOMINATION DEADLINE OCTOBER 15

For nomination details visit: *asme.org/about-asme/honors-awards/unit-awards#igti*

Nominating letters should contain all information on the nominee's relevant qualifications. The Award Committee will not solicit or consider materials other than those described below. The selection committee will hold nominations active for a period of three years. A minimum of two supporting letters from individuals, other than the nominator, must accompany the nominating letter. Including a CV would be appreciated. Supporting letters should reflect peer recognition of the nominee's breadth of experience with various aspects of industrial gas turbine technology.

ASME IGTI DILIP R. BALLAL EARLY CAREER AWARD

NOMINATION DEADLINE AUGUST 1

For nomination details visit: *asme.org/about-asme/honors-awards/unit-awards#igti*

The nomination package should include the following:

- A paragraph (less than 50 words) from the nominator highlighting nominee's contributions
- Nomination letter
- Two supporting letters
- Current resume of the nominee

ASME IGTI INDUSTRIAL GAS TURBINE TECHNOLOGY AWARD

NOMINATION DEADLINE OCTOBER 15

For nomination details visit: *asme.org/about-asme/honors-awards/unit-awards#igti*

Nominating letters should contain all information on the nominee's relevant qualifications. The Award Committee will not solicit or consider materials other than those described below. The selection committee will hold nominations active for a period of three years. A minimum of two supporting letters from individuals, other than the nominator, must accompany the nominating letter. Including a CV would be appreciated. Supporting letters should reflect peer recognition of the nominee's breadth of experience with various aspects of industrial gas turbine technology.

ASME R. TOM SAWYER AWARD

NOMINATION DEADLINE AUGUST 15

For nomination details visit: *asme.org/about-asme/honors-awards/achievement-awards/r-tom-sawyer-award*

The nomination must be complete and accompanied by three to five Letters of Recommendation from individuals who are well acquainted with the nominees' qualifications. Candidate nominations remain in effect for three years and are automatically carried over. The completed reference form from a minimum of 3 people will need to be sent in with the nomination package. It is up to the "Nominator" to submit all required information.

QUESTIONS MAY BE SENT TO IGTIAWARDS@ASME.ORG.

CLICK HERE FOR ADDITIONAL RESOURCES FOR THE ASME INTERNATIONAL GAS TURBINE HONORS AND AWARDS OPPORTUNITIES

ASME Turbo Expo Conference and Exhibition

JUNE 24-28, 2024
EXCEL LONDON, LONDON, ENGLAND, UNITED KINGDOM

This year top experts and decision-makers will gather in-person to exchange ideas and experiences to develop and discuss the implementation of safe, reliable carbon neutral solutions while shaping the future of the turbomachinery industry. Turbo Expo will serve as a synergetic platform for government, academic, research, and industry professionals to discuss multidisciplinary approaches for decarbonization.

The 5-day conference will include 1000+ technical presentations, tutorials, and panels. The conference offers a series of unopposed plenary sessions highlighting the Turbo Expo 2024 theme, Achievements and Needs to Unlock a Net-Zero Future in Propulsion and Power.

Monday's Keynote

Accelerating the Transition in Innovation and Technology Towards a Net-Zero

Tuesday's Plenary

World Achievements to Date Towards Net-Zero in Propulsion and Power

Wednesday's Plenary

Supporting Measures and Technologies Required to Deliver on Net-Zero Targets

In Addition,

Turbo Expo 2024 will hold a 3-day exhibition featuring professionals ready to share their products and services with the turbomachinery industry. The exhibition running Tuesday to Thursday will showcase afternoon open hosted receptions allowing attendees to build out their professional network and identify future opportunities. The exhibit hall also hosts:

TURBO EXPO'S STUDENT POSTER COMPETITION

The competition is organized by the Student Advisory Committee for students contributing to the advancements in turbomachinery.

THE CELEBRATING WOMEN IN TURBOMACHINERY

Wednesday Evening

This networking event will feature motivating talks. Attendees will have the opportunity to network and learn about the career paths of successful women in the industry.

TURBO EXPO WELCOME RECEPTION

Monday Night

Kickstart your week by catching up with colleagues and making new connections over light refreshments.

EARLY CAREER ENGINEER MIXER

Sunday Evening

Meet with students and early career engineers. The collaborative atmosphere of this event is ideal to meet thinkers from around the world who are shaping the future of the turbomachinery industry. This is the ideal event for attendees in the process of developing their careers.

To learn more, visit the Turbo Expo 2024 website and register today.