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A Novel Test Bed for the Aeroacoustic Investigation of UCAV Configurations with Highly Integrated Propulsion Systems

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In this contribution, a novel test bed designed for the experimental investigation of the acoustic signature of unmanned combat air vehicle with highly integrated propulsion systems is presented. The model integrates a curved intake duct design as well as a curved, high aspect ratio, rectangular nozzle design. Operation of the model in suction mode or pressurized mode allow investigations of the intake and nozzle acoustics independently and in a realistic Mach number range, e.g. Ma=0.4 in the intake duct and Ma=0.75 in the jet. Intake sound emissions are found to have a directivity peaking in the forward arc which is strongly dependent on the suction mass flow rate and almost independent of the free-stream Mach number. The jet is found to radiate sound with a rear arc directivity for model scale frequencies above 3.15 kHz. The acoustic is also a strong function of the nozzle mass flow rate only. The overall shape of the jet acoustic directivity suggests the existence of two source component aligned at 90° and 140° to the upstream direction, respectively.

I. Introduction

In this paper we present a novel wind tunnel test bed for the aeroacoustic assessment of realistic UCAV configurations with highly integrated propulsion systems. This work is the continuation of earlier work done at more generic configurations [1] in the framework of the NATO STO AVT-233 group, dealing with the aeroacoustics of Engine/Rotor installation for Military Air Vehicles. In that effort, the acoustic shielding properties of the SACCON UCAV (Stability And Control CONfiguration) planform were investigated. More specifically experiments were done, using a generic sound source, to quantify acoustic shielding by the airframe. The focus of the experiment was put on the quantification of the acoustic attenuation by the airframe as a function of engine placement i.e. source position. The main purpose of these tests was to put a database together, appropriate for the validation of aeroacoustic numerical simulation tools. The current contribution is done as part of the NATO STO AVT-318 group (Low noise aeroacoustic design for turbofan powered NATO air vehicles), which extends the work started on this topic to now deal with realistic sources on a concurrent agile (unmanned) NATO air vehicle design, the MULDICON UCAV configuration (MULti-Disciplinary CONfiguration),

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This novel experimental setup will enable the generation of a unique validation database necessary for the evaluation and qualification of efficient and accurate numerical assessment methodologies. Although aeroacoustic simulation methodologies have been extensively validated and their state of development is mature, their application to UAV/UCAV configurations assessment is novel. Therefore, the aeroacoustic assessment of these vehicles is currently not part of the design chain, but comes as a by-product when the configuration is fixed. There is, therefore, a technological interest in the evaluation of current aeroacoustic prediction methodologies and their further development, with respect to UAV/UCAV applications. Specifically, for UCAV, the advance of aeroacoustic simulation methodologies will lead to enhance capabilities in terms of low noise mission planning, minimizing the risk of early acoustic detection.

A highly relevant technical question, in term of the acoustic signature of UCAVs, concerns the engine integration into the airframe. The actual position of the engine relative to an aircraft's planform is known to directly impact its acoustic signature [2, 3, 4, 5]. Moreover, for jet-propelled vehicles, the specific characteristics of the exhaust jet also have a strong impact on the vehicle's acoustic signature, in terms of absolute noise emission levels and directivity [5]. Further, the question of the integration of the propulsion system also requires dealing with the geometrical design of the intake and exhaust ducts. This topic is highly relevant for radar detection, which mostly drives the designs of curved intakes and exhausts to minimize radar detectability. This type of intake duct poses great challenges for engine design due to stronger flow non-uniformity upstream of the engine. The resulting impact of this kind of specialized configuration on the acoustic signature requires further investigation. Finally, aspects of noise mitigation could further help in reducing the acoustic signature of UCAVs.

The aim of this new test facility is to provide the means to produce a high-quality database on the acoustic signature of realistic UCAV configurations with highly integrated propulsion systems. The acquired data will enable the testing and validation of aeroacoustic numerical simulation methodologies while also revealing important physical insights on the relevant sources of aeroacoustic sound. The resulting physical understanding will allow to put forward better design guidelines and elaborate appropriate noise mitigation technologies.

II. DLR-F24 Muldicon Acoustic UCAV Demonstrator

A. Planform Origin's

The original MULDICON configuration was developed in the framework of NATO STO Task Group AVT-251 (Conceptual UCAV Design). The aim of this Task Group was to perform an aerodynamic re-design of the SACCON UCAV, only through the use of flow simulations methods i.e. CFD. This was made possible through knowledge gained throughout earlier Task Groups. In AVT-161, the ability of computational methods to accurately predict static and dynamic stability was evaluated. The AVT-201 task group aimed at including control surfaces in the aerodynamic assessment as well as investigating ways to perform full flight simulations [6]. AVT-251 was not about designing a competitive UCAV but rather aimed at improving SACCON while making it a realistic, flyable, vehicle. To achieve this goal SACCON was first evaluated with respect to its ability to fulfil a flight mission, i.e. prescribed flight trajectory at a given altitude of 11 km and Mach number of 0.8 for a given payload [6]. The result of this evaluation emphasized the poor control characteristics of SACCON, due to the high-sweep design of its trailing edges. This led the group to design a new configuration, MULDICON, circumventing the issues encountered with SACCON.

B. DLR-F24 Muldicon Design

The experimental setup is designed around the concurrent agile (unmanned) NATO air vehicle design, the MULDICON UCAV configuration (MULti-Disciplinary CONfiguration) [6], e.g. Figure 3. The original MULDICON UCAV planform design, which origins from NATO AVT-251 [6], was adopted and modified to allow, from an experimental standpoint, the integration of an intake and an exhaust channel, as depicted in Figure 3. The original planform remained untouched while the centerbody design by FOI (Swedish Defense Research Agency) was selected [3]. This design has a thicker centerbody, leaving more room for the intake and exhaust channels integration.

The design allows for the realization of a controlled high-velocity intake flow as well as a cold high-velocity exhaust jet; through a connection to a suction air system or a pressurized air supply, respectively. An intake suction mass-flow rate on the order of 0.9 kg/s was achieved in the experiments while a mass-flow rate on the order of 1.8 kg/s, corresponding to an estimated jet Mach number of 0.8, can be reached at the nozzle. The model is equipped with 58 surface pressure taps to acquire aerodynamic loads as well as total pressure ports to monitor the model internal plenum pressure.

The test bed was specifically design for testing in the anechoic test section of the low-speed acoustic wind tunnel of DNW in Braunschweig (NWB) (e.g. Figure 7), and thus for subsonic test conditions up to a Mach number of 0.2. The centerbody and intake are based on a design by FOI [3], while the nozzle is a DLR-design. The complex curved intake and nozzle geometries were designed with radar signature minimization in mind, with no a priori consideration of the acoustic radiation problem.

The overall design of the DLR-F24 Muldicon model is highly modular to allow the intake, nozzle and internals to be easily modified or be replaced by other designs. This is especially interesting with regards to the evaluation of noise mitigation technologies and also adds some flexibility in dealing with various experimental measurement technique requirements. The main components of the model are displayed in Figure 2. Both the intake and nozzle were fabricated through rapid prototyping techniques and painted to obtain a smooth surface finish. The middle part of the model consists of the internal plenum which accessible through rectangular opening on the upper and lower side. On each side of the central plenum, two openings provide the interface where pressurized air or suction air can be apply to the model. The connection to the wind tunnel compressor system occurs through the horizontal holder shown in Figure 7.

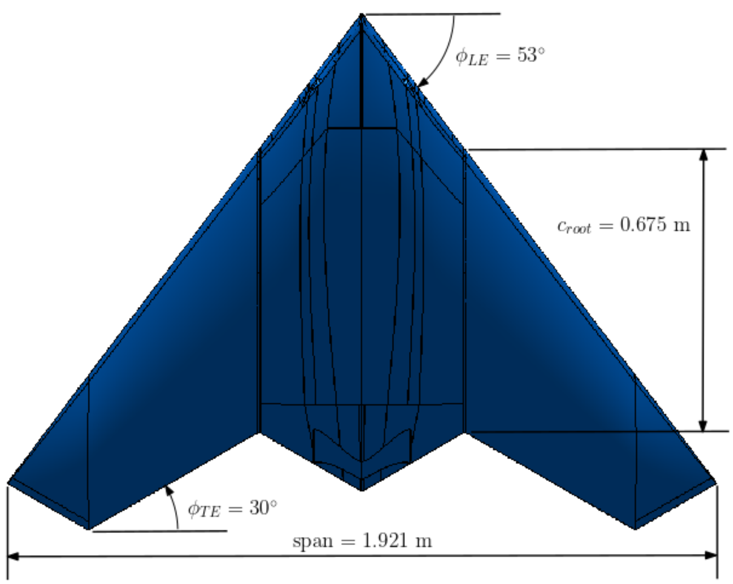


Figure 1. DLR-F24 Muldicon planform geometry [6]

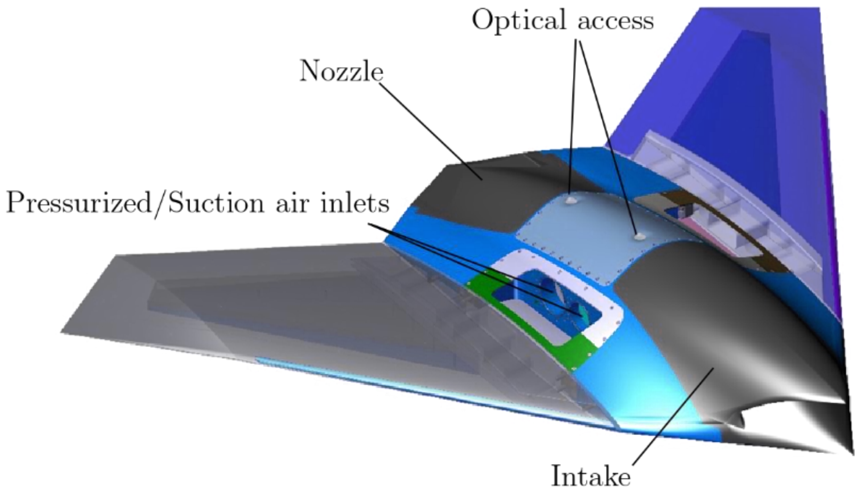
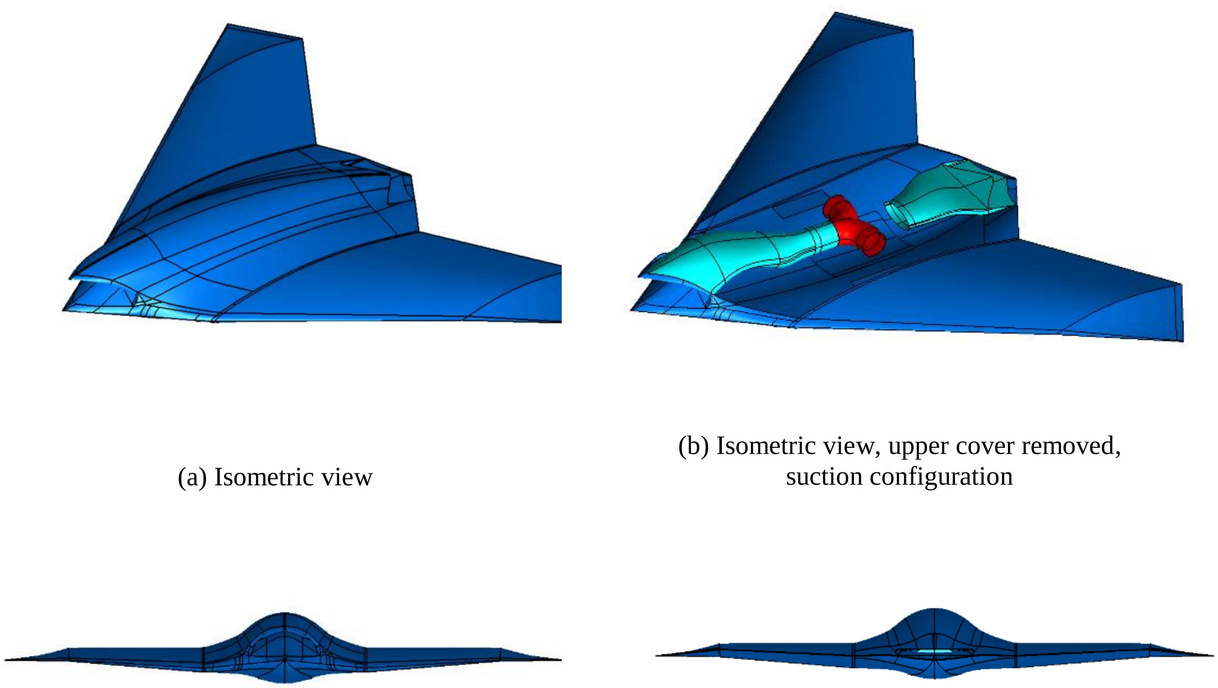


Figure 2. DLR-F24 Modular design. View of optical access ports and presurized air inlets.

Different perspectives on the model are given in Figure 3. In particular, Figure 3b gives an isometric view of the model with its upper part removed to reveal details of the internal connections of the intake duct to the pressurized air system, e.g. shown in red. The decision to split the intake duct, inside the model center chamber, is an attempt to keep the duct velocities near the model's outlet to the compressor system as low as possible and thus keep any spurious source of noise as low as possible.



(a) Isometric view

(b) Isometric view, upper cover removed, suction configuration

(c) Front view (intake duct)

(d) Back view (nozzle)

Figure 3. DLR-F24 MULDICON UCAV model views

Detailed views of the model's internal chamber in the jet mode and suction mode configurations are presented in Figure 4. The direction of airflow in these configurations is indicated by the arrows. In the jet mode configuration, e.g. Figure 4a, the horizontal holders provide pressurized air through the upstream most opening in the chamber side walls, e.g. Figure 2. The flow of compressed air is first forced through porous aluminum sound absorber where most up the upstream spurious noise is dampened. A flow straightener installed in the center of the chamber helps in uniformizing the flow before reaching the nozzle. The nozzle itself has an elliptical cross-section at the interface with the center chamber which evolve to a rectangular cross-section towards the exit plane. The exit plane cross-section has a width of 266 mm and a height of 20 mm corresponding to an aspect ratio of 13.3, e.g. Figure 6. In the suction mode configuration, e.g. Figure 4b, suction is applied through the horizontal holder at the rear most opening in the chamber side walls, e.g. Figure 2. The rear part of the intake duct, before the splitter, is designed to have a constant cross-section of 76 mm in diameter. It is equipped with an optical access port to allow the use of a laser-based sound source to trigger propagating acoustic duct modes inside of the intake. Details about the laser sound source technique have been published elsewhere and can be found in references [7, 8, 9]. Thus, enabling the investigation of the effect of the intake flow on the propagation of acoustic duct modes. A cross-cut view through the model center is shown in Figure 5, making visible the arrangement of all components and the detailed contours of the intake duct and nozzle. The section area distribution of the intake duct and nozzle are given in Figure 6. Both ducts have converging cross-section area.

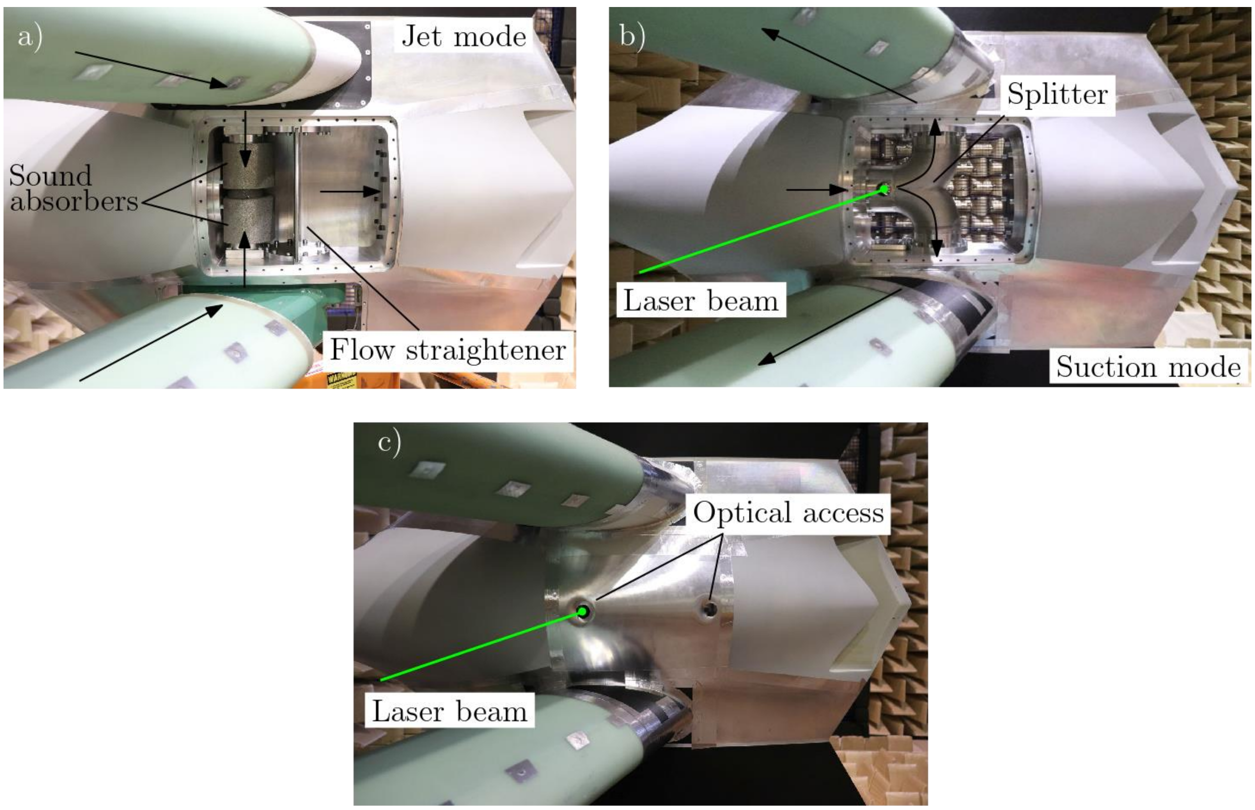


Figure 4. View of the model's plenum in a) jet mode configuration, b) suction mode configuration and c) with its upper cover installed. In a) and b) the arrows indicated the directions of the internal stream of air.

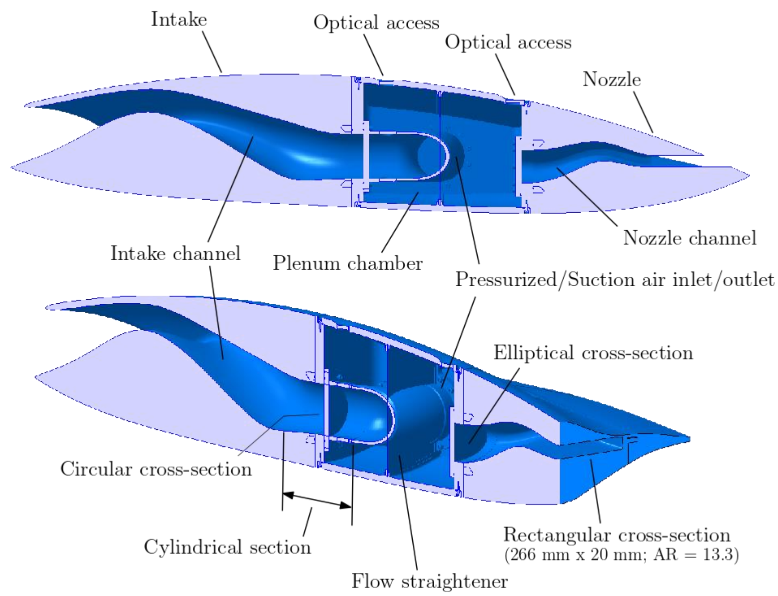


Figure 5. CAD details of the intake, nozzle and plenum geometries with the splitter junction and flow straightener installed.

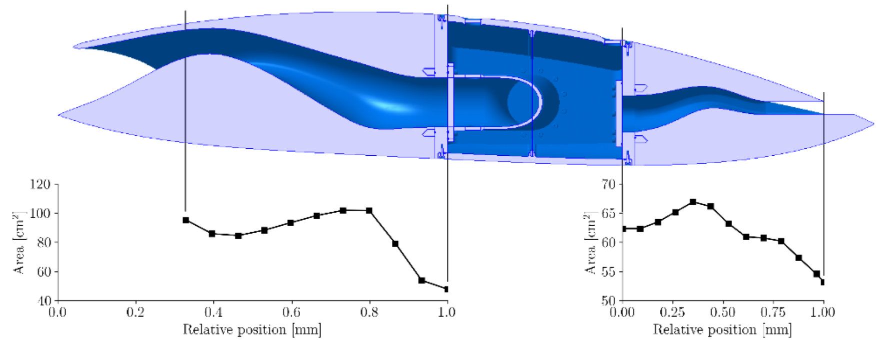


Figure 6. Intake and nozzle ducts section area distribution

III. Experimental Setup in DNW-NWB

The DLR-F24 Muldicon model was specifically designed for use in the anechoic test section of the NWB. The NWB has nozzle surface of 3.25 m x 2.8 m and a test section length of 6 m. Its acoustic plenum has dimensions 14 m x 16 m x 8 m (length x width x height) and is certified for a frequency range of 100 Hz to 40 kHz in accordance with Appendix A of ISO 3745. The wind tunnel, in the open jet configuration, can be operated at free-stream velocities up to 80 m/s. Pressurized air or suction air can be supplied to the model through the NWB's own compressors system.

An overview of the complete experimental setup in the test section of the NWB is provided in Figure 7. This figure includes the inflow microphone setup, the laser tower and the model's support rig. The support rig, consist of an oversized L-shaped construction where the two elliptically-shaped horizontal model holders attach. The horizontal holders connect to the pressurized air circuit through pipes mounted to the back side of the rig. The stable construction of the rig was necessary to ensure repeatable positioning of the laser sound source inside the intake duct. The model is mounted vertically in the test section. This allows for free space on the model's lower side where acoustic field is to be acquired. At the same time, it provides a certain amount of shielding form spurious source of noise on the upper side, e.g. flow noise through interaction with the horizontal holders. The L-rig is mounted directly onto NWB's turntable, making small adjustment in angle of attack possible; although the model was not design to withstand wing loads occurring above an angle of attack of 5°. The horizontal holders were designed with an elliptic contour to help limit their effect on the free-stream; although their influence on the flow in the close proximity of the model's upper surface is clearly apparent from flow visualizations made in the course of the experiments.

This design choice constitutes a compromise allowing a very stable model fixation through the rig's stiffness while promoting lower flow velocities in the pressurized pipe system prior to reaching the model. Moreover, the horizontal holders are tilted by 15° in the upstream direction to reduce the influence of the tunnel shear-layers on the structure and keep the holder length as short as possible. This rotation also effectively reduces the chordwise velocity near the trailing edge and thus, also reducing trailing noise radiation.

The acoustic emissions of the model in its various configurations are acquired by a set of four in-flow microphones mounted to a linear displacement system. When using the laser sound source, four 1/8" GRAS 40 DP microphones are used. Otherwise four ¼" GRAS 46BF-1 free-field microphone provided by NWB were used. NWB's 160 microphone phased array mounted to a second linear traversing stage, is used as a complementary measurement technique; primarily for source identification. Specific details regarding the microphone setup and measurement ranges are provided in Figure 8.

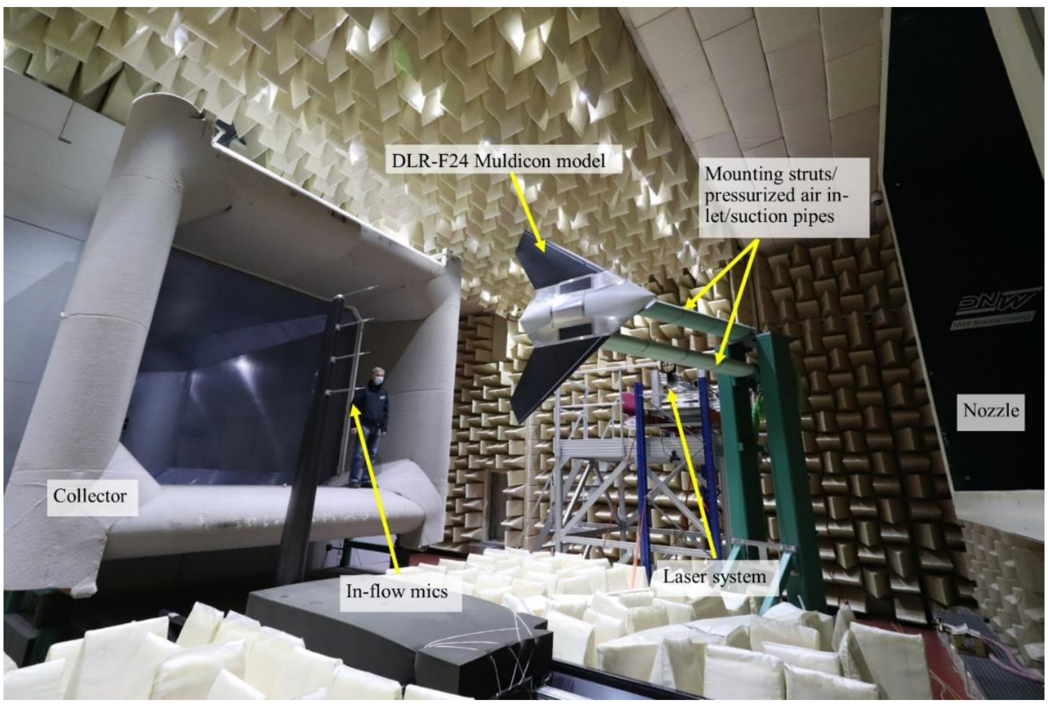


Figure 7. DLR-F24 MULDICON test bed in the open-jet acoustic test section of DNW-NWB. The flow direction is from right to left.

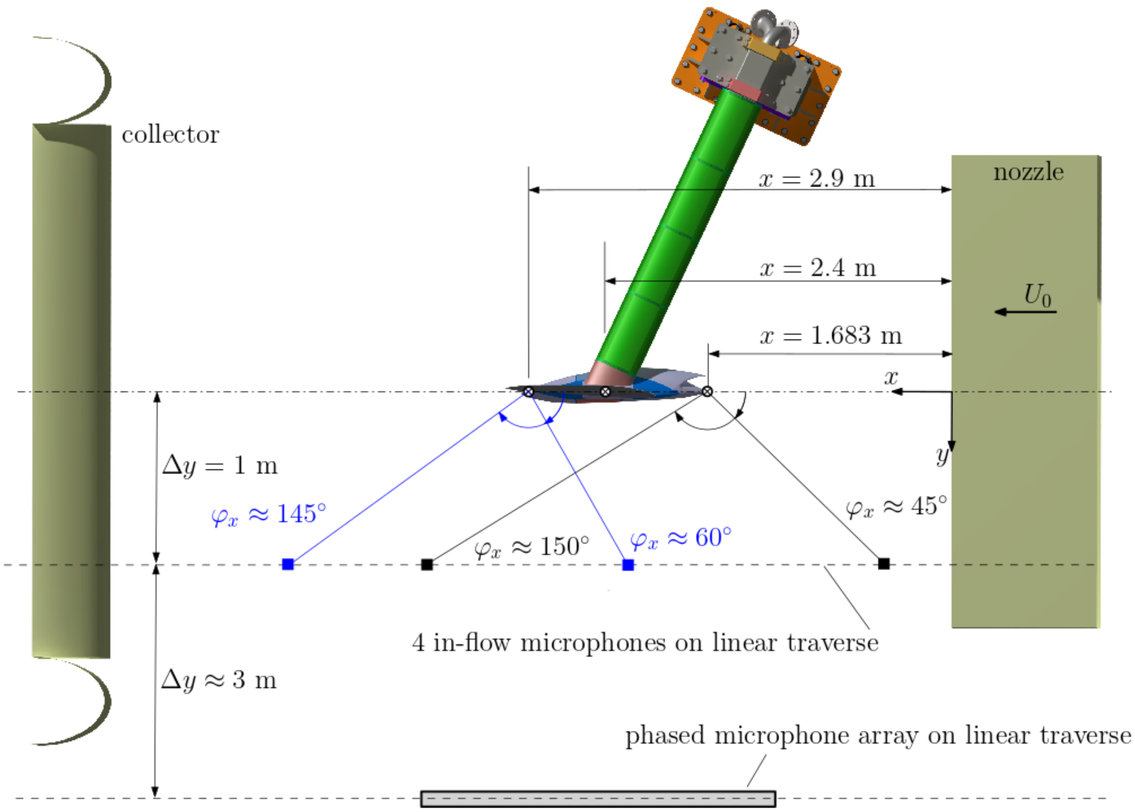


Figure 8. Experimental setup in NWB. The range indicated in black and blue correspond to the in-flow measurements ranges for the intake acoustic and jet acoustic, respectively.

IV. Acoustic Signature

In this section early analysis of both the intake and jet noise radiation of the DLR-F24 Muldicon model are presented, in terms of their source directivity. Further and more refined analysis are outside the scope of the present paper.

A. Intake Acoustics

The parameters of interest for the experiment included variations in upstream Mach number, variations in suction mass flow rate and combinations of both. Furthermore, the model is equipped with optical ports to allow the use of a laser-based impulsive point-like sound source to generate pressure pulses in the intake duct. Thus, using this technique, acoustic propagating modes can be triggered inside the duct and the corresponding acoustic free-field radiation is acquired by the in-flow microphones.

Third octave band directivity data for frequencies $f_{c,1/3} = 0.8, 4, 10, 40$ kHz are given in Figure 9 as a function of free-stream Mach number and suction mass flow rate. In this figure, the sound radiation from the laser based sound source is given in black, airframe noise is given in green and suction noise in blue. At the 4 kHz third-octave band suction and airframe sound approximately reach their peak amplitude, whereas the laser sound source peaks in the 40 kHz third-octave band. The emitted intake's sound directivity is found to have its maximum towards the upstream direction at angles below or equal to $\varphi_x = 45°$, regardless of the operating conditions considered in the experiments. Airframe noise, on the contrary, is almost omni-directional.

The parametric dependence of the laser-induced intake sound on the free-stream Mach number and mass flow rate is presented in Figure 10 for a third octave band frequency of $f_{c,1/3} = 40$ kHz; frequency at which laser sound's reaches its peak. The results of Figure 10 demonstrate that convection effects through variations of the free-stream velocity do not affect the directivity of intake sound nor does it affect its absolute level. The most important factor influencing the acoustic emissions is the suction mass flow rate, which potentially affects both the directionality and absolute sound pressure level.

B. Jet Acoustics

Results for the jet acoustic radiation as a function of the free-stream Mach number and jet mass flow rate are presented in Figure 11. At the lowest one-third octave band frequencies considered herein, in Figure 11a,b, jet noise appears to reach its maximum sound pressure level at an approximative angle $\varphi_x = 105°$. Variations in free-stream Mach number or nozzle mass flow rate only have a minor effect on the absolute acoustic radiation levels; as if some cut-off conditions were met. From $f_{c,1/3} = 3.15$ kHz up to $f_{c,1/3} = 10$ kHz, the acoustic data are found to depend strongly, and almost exclusively on the nozzle mass flow rate. The overall directionality of the sound at $f_{c,1/3} = 3.15$ kHz and $f_{c,1/3} = 4$ kHz, suggest a combination of two main source components, one aligned with the $\varphi_x = 105°$ direction and a second one aligned with the $\varphi_x = 140°$ direction. At $f_{c,1/3} = 6.3$ kHz and $f_{c,1/3} = 10$ kHz, the first component loses in intensity compared to the second one, giving rise to a typical rearward-oriented jet noise maximum. These observations are somewhat unexpected and need further investigation to be clarified. They could be characteristic of the type of nozzle considered in the investigation.

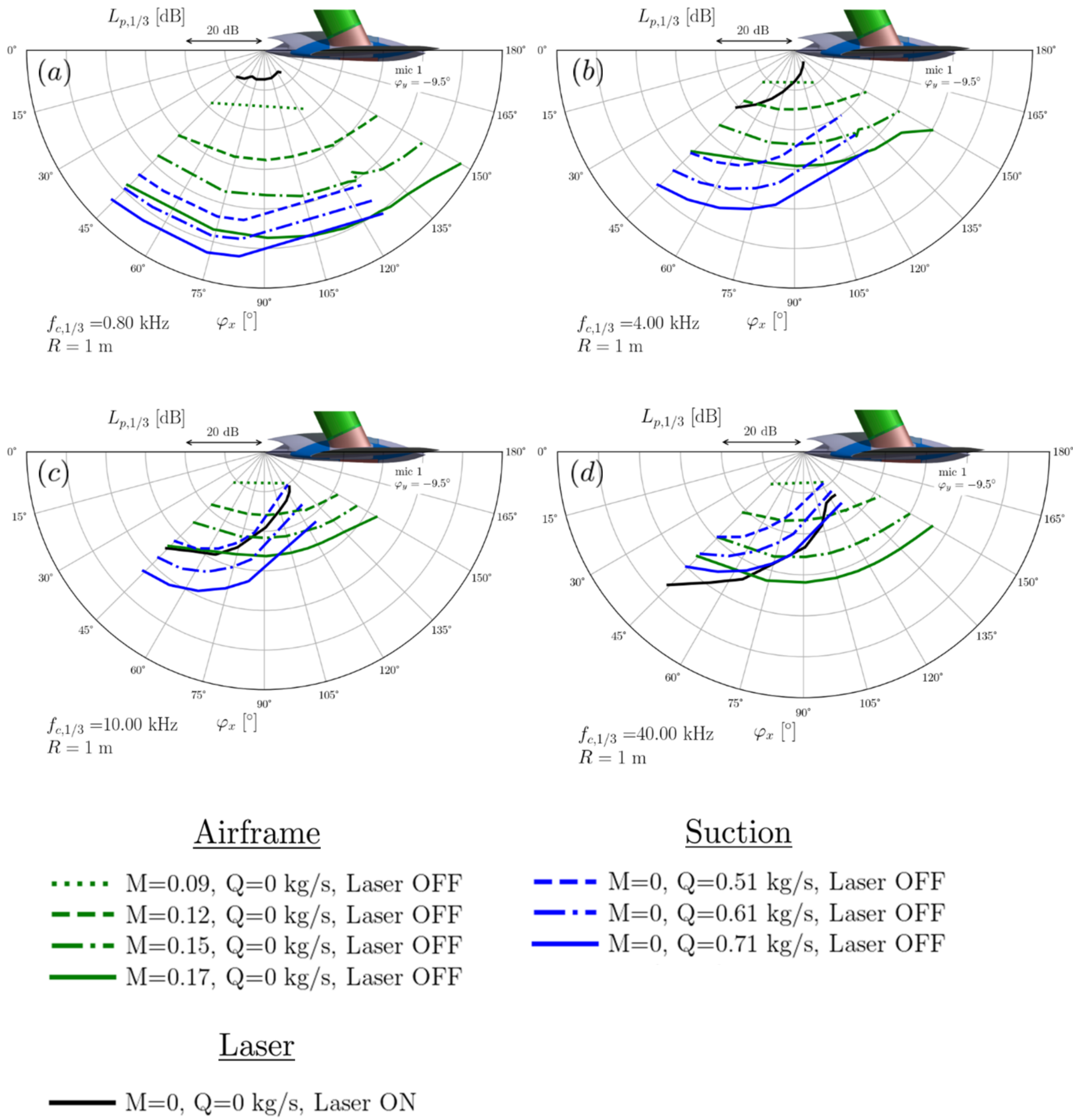


Figure 9. Intake sound radiation vs. free-stream Mach number (M) and suction mass flow rate (Q) for selected third octave band frequencies.

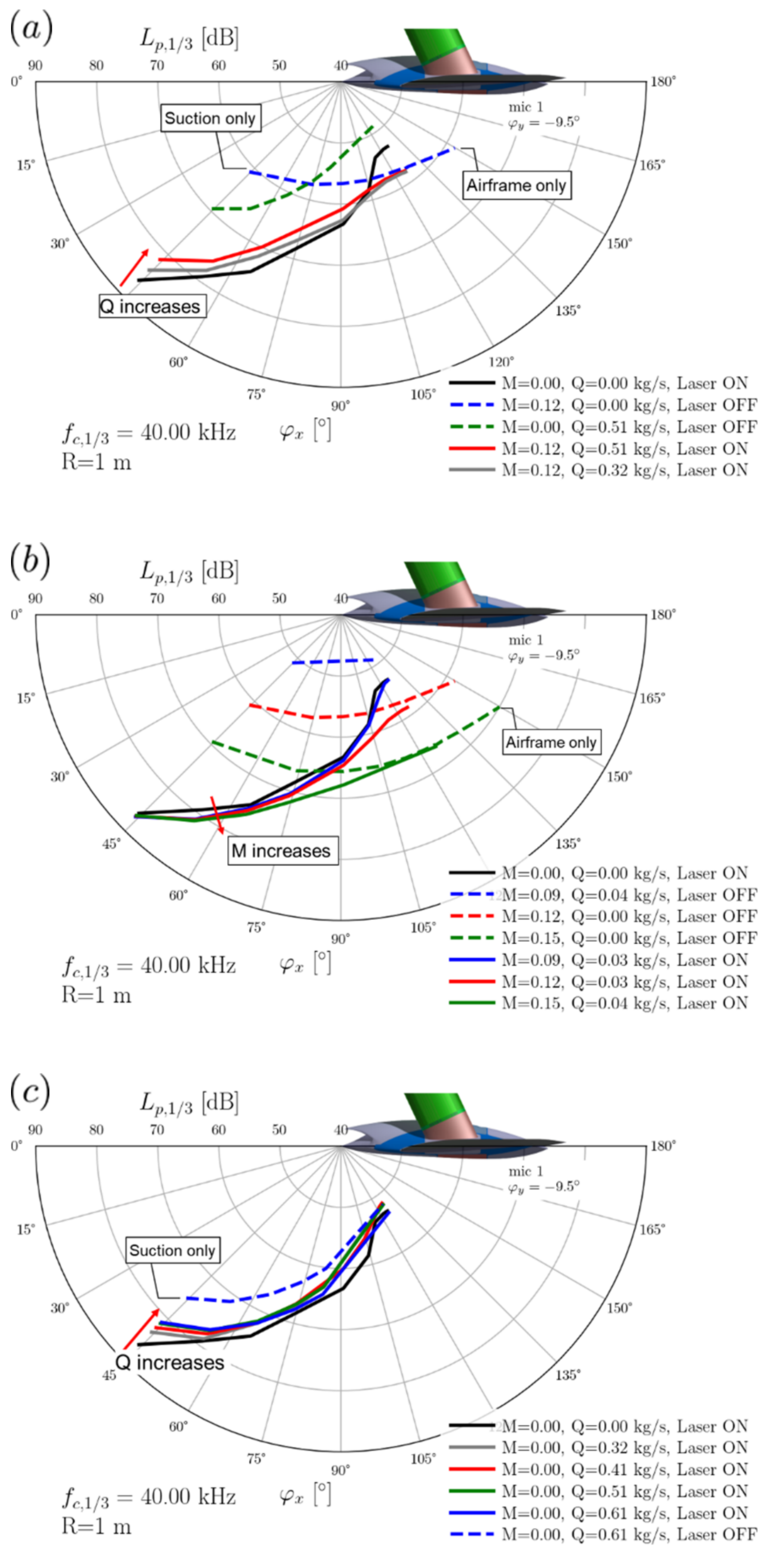


Figure 10. Effect of the free-stream Mach number (M) and mass flow rate (Q) on laser induced intake sound radiation. $f_{c,1/3} = 40$ kHz.

V. Conclusions

In this contribution, a novel test bed designed for the experimental investigation of the acoustic signature of unmanned combat air vehicle with highly integrated propulsion systems is presented. The DLR-F24 Muldicon wind tunnel model is introduced which is based on a planform design developed in the framework of the NATO Task group AVT-251. The model integrated the curved intake duct design of the Swedish Defense Research Agency (FOI) as well as a curved, high aspect ratio, rectangular nozzle design. The model is designed in a modular fashion to allow easy configuration changes. Operation of the model in suction mode or pressurized mode allow investigations of the intake and nozzle acoustics independently and in a realistic Mach number range, e.g. Ma=0.4 in the intake duct and Ma=0.8 in the jet. Optical access ports enable the used of a laser based impulsive sound to generate point-like sound waves inside the intake duct to trigger propagating acoustic duct modes. Selected results from investigations conducted in the low speed anechoic wind tunnel of DNW are presented. Intake sound emissions are found to have a directivity peaking in the forward arc which is strongly dependent on the suction mass flow rate and almost independent of the free-stream Mach number. The jet is found to radiate sound with a rear arc directivity for model scale frequencies above 3.15 kHz. The acoustic is also a strong function of the nozzle mass flow rate only. The overall shape of the jet acoustic directivity suggests the existence of two source component aligned at 90° and 140° to the upstream direction, respectively.

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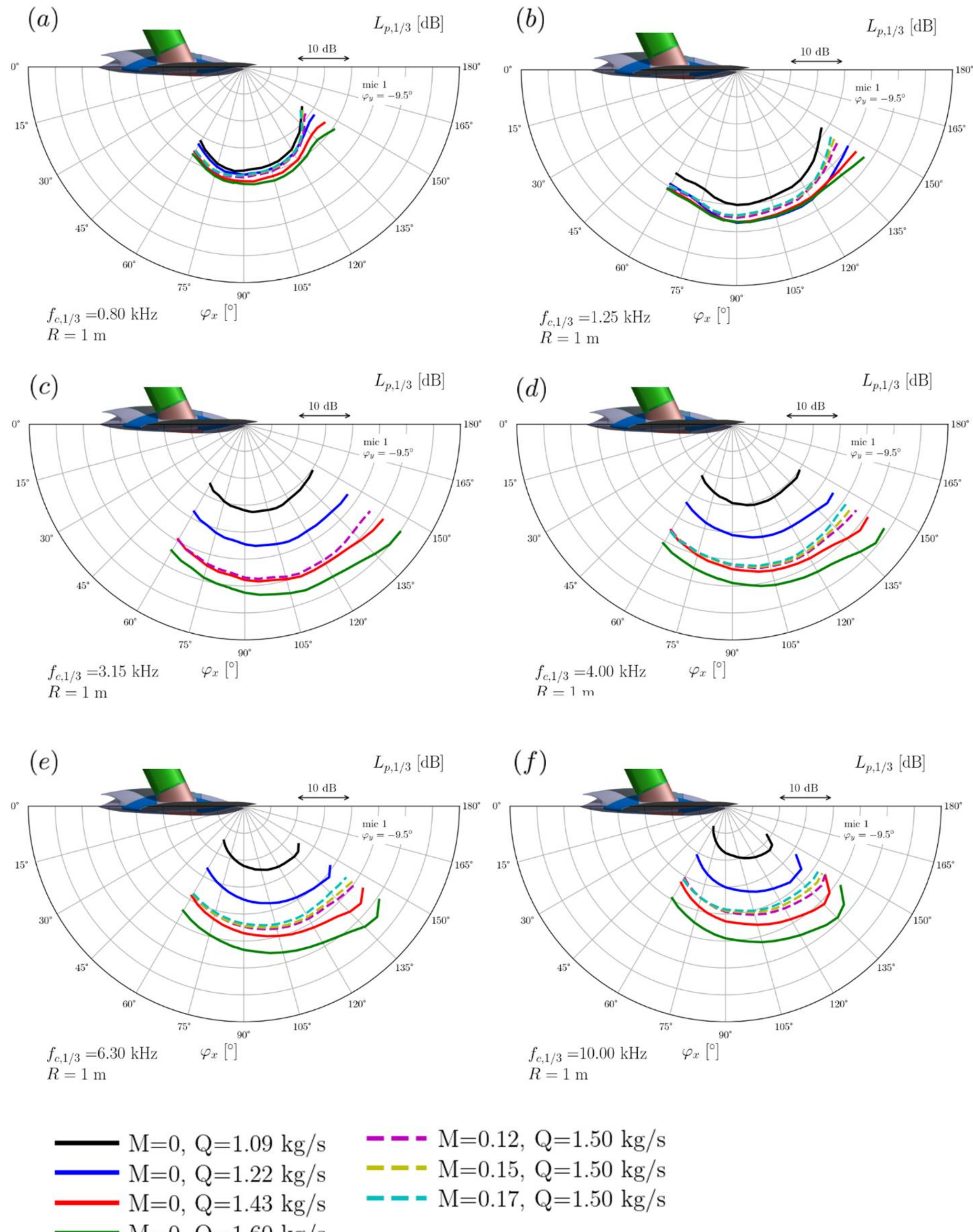

Figure 11. Jet noise directivity 9.5° to the sideline vs. free stream Mach number (M) and jet mass flow rate (Q) and for selected third octave band frequencies.

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