EAA
European Acoustics Association

EuroRegio2016
June 13-15, 2016
Porto · Portugal

VALIDATION OF NOISE MODEL FOR A HIGH PERFORMANCE MILITARY AIRCRAFT

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Abstract

This paper gives a survey of the approaches and results concerning validation of the noise models developed within the framework of a medium-term initiative at Airbus Defence and Space GmbH to reduce the noise produced by high performance military aircraft. Based on a modular approach a widely generic model has been developed for estimation of the noise characteristics for the different noise sources identified (e.g. jet, fan, landing gear). However most of these separate noise models have been synthesized mainly based on theoretical/textbook approaches inducing the need for according (flight test) validation. Due to the complexity of the overall model as a first step an appropriate validation strategy had to be defined which finally led to an according flight test plan. Subsequently aircraft noise flight test data gathering had been performed supported by the company Brüel&Kjær which then provided to Airbus information on noise emission and directivity characteristics for the different noise sources modelled. Using these data the existing noise source models will be refined in order to better reflect reality and thus building a reliable basis for calculating the overall noise emitted. In combination with the yet started validation of the according noise propagation algorithm this will result in an overall validated model for calculating on-ground noise immissions of an aircraft during flight.

Keywords: aircraft noise, noise reduction, noise sources, validation.

PACS no. 43.50.Lj, 43.50.Nm

1 Introduction

Noise reduction for civil aircraft has been an important issue for aircraft manufacturers as well as for airport operators within the last decades. Meanwhile a huge set of requirements and rules coming from annoyed residents, legal regulations, and customers, i.e. airline companies have to be taken into consideration. However for a long time less emphasis has been placed on noise reduction for military aircraft due to several reasons. As can be depicted from Fig. 1 this seems to be subject to change over the past years and also military aircraft noise becomes more important as the number of hits for the search expressions ‘Aircraft Noise’ and ‘Military Aircraft Noise’ in a scientific article database exemplarily shows.

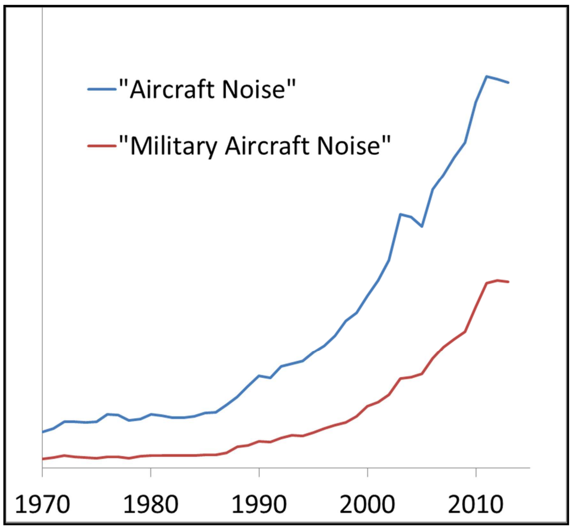


Figure 1 – Search results in scientific article database.

Additionally the respective international regulations [1] have been tightened in two steps in 1985 and quite recently in 2006. Similar regulations on European and national (e.g. German) level exist. Accordingly the relevant regulations are

- ICAO Annex 16, Volume 1, Para 12.2 and 3.4.1.2a (international)
- EC Regulation 1592/2002, Articles 6 and 13 (european)
- LuftVZO, Article 3 (german).

For military aircraft specifically there is also a certain shift in emphasis with respect to the relevance of noise emissions to be observed. Whereas in the past national fighter acquisition programs usually contained no requirements with respect to noise emission/immission, especially in the last decade the according Requests for Information or Proposal (RfI/RfP) more frequently ask for respective data and information.

This can be illustrated e.g. by an article [2] in the Swiss public journal ‘Cockpit’ on the latest Swiss Air Force Fighter acquisition program where finally the Swiss representative ‘armasuisse’ together with the respective tenderers performed according flight tests which subsequently were evaluated by the Swiss institute EMPA.

These facts finally lead obviously to the necessity of developing strategies and technical solutions for (military) aircraft noise abatement.

In the paper proposed here the overall approach and actual status of an industrial noise reduction initiative for a specific high performance military aircraft is presented. However as the according processes and techniques developed are by their very nature generic to a large extent application to other aircraft (types) would be straightforward in principle.

As aspects of noise reduction nevertheless still are of minor importance for the design and development of military aircraft especially compared to operational requirements the focus for the approach presented here has been mainly placed on noise immission rather than emission. As obviously the predominant nuisance generated by aircraft is in the vicinity of the respective airfields the overall goal defined is the

Reduction of aircraft noise ground immission by optimization of the according takeoff climb (and landing approach) flight paths.

2 Overall Approach

Pursuing the above goal it is finally necessary to implement an optimization algorithm which generates noise optimal (minimal) flight paths based on dedicated suitable optimization criterions (noise metrics). Main focus has to be put on allowance of a broad variety of possible flight paths and easy observance of boundary conditions (e.g. flight mechanical/performance restrictions, terrain information, and residential or prohibited areas respectively) whereas accuracy of the solution will be only a subordinate goal. From the current point of view therefore e.g. the use of the principles of genetic optimization seems to be appropriate. Developing and subsequently implementing an according algorithm is however a very time consuming task and will therefore be accomplished towards the end of the whole program development cycle. For the time being the definition and construction of operationally reasonable flight paths 'by hand' e.g. based on operational manual or flight test data or a combination of both should be sufficient. An overview over the main elements of the general overall approach for noise minimization can be found in Fig. 2.

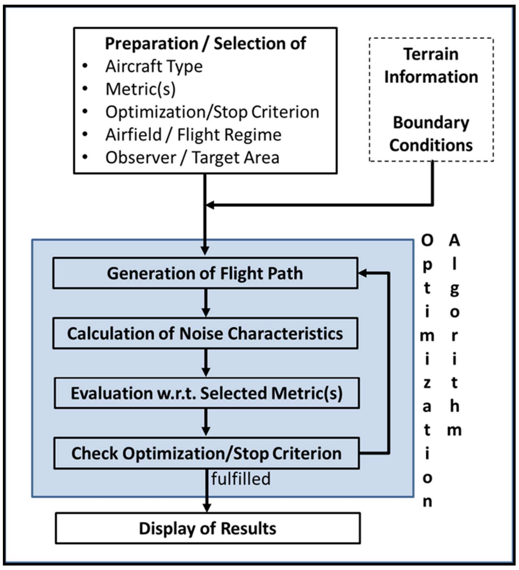


Figure 2 – Logic of overall approach.

The starting point 'Selection of Aircraft' stresses the modular nature of the approach presented here. All aircraft specific parameters (e.g. for engine or aerodynamics) are not hard-coded but are provided to the program by dedicated external datasets using respective generic interfaces.

One crucial point for a proper setting of an optimization approach is the appropriate choice of the respective metric(s) for the evaluation of noise on ground. Accordingly a respective comprehensive literature study has been undertaken in order to identify the most suitable metrics. In addition to a total of 14 psychoacoustic metrics which are not taken into account at the current stage of the development, the following 'objective' metrics have been assessed to be suitable for comparative noise immission evaluation.

- (A-weighted) Sound Pressure Level
- Sound Exposure Level
- Equivalent Continuous Sound Level
- Time Above Specific Level
- Day-and-Night Equivalent Sound Level
- (Effective) Perceived Noise Level

In the module 'Selection of Optimization/Stop Criterion' it is fixed whether one single optimal solution or rather a set of feasible flight paths fulfilling e.g. according accuracy requirements is searched for. Additionally the maximum number of iterations is set.

Furthermore in 'Selection of Airfield' the local coordinate system is fixed by choosing a geographic point (in WGS 84 / NAVSTAR GPS coordinates) representing the airfield the takeoff (or landing) is performed on. Additionally the position of the observer or an appropriate area on ground is defined for which the chosen noise metric(s) shall be evaluated.

Prior to the start of the actual optimization algorithm additional information on terrain specifics and possible boundary conditions (e.g. residential or restricted areas) represented by accordingly defined data bases are fed into the program via respective modularly designed interfaces.

The first step within the optimization algorithm will be the selection or generation of a dedicated flight path being a candidate for the optimum solution to be found. After the calculation of the noise characteristics along the flight path the above chosen on-ground noise metrics have to be evaluated thus providing a basis for the subsequent decision on continuation of the optimization iteration. In case optimisation is continued a new 'candidate' flight path has to be constructed based on previous results (feedback loop). The methods and principles which are applied for this purpose are constituting the very core of an optimization approach/algorithm.

If the stop criterion is fulfilled the results will be displayed using a dedicated user interface. Furthermore all relevant and necessary data for a potential post processing (e.g. detailed analysis of feasible flight paths) are stored in accordingly designed data bases.

3 Noise Calculation Model

However, basis for the above mentioned optimization approach has to be obviously a **validated** (modular) aircraft noise calculation model consisting of the three main components

- **emission** (analytic modular approach)
- **transmission** (modified/simplified ray tracing)
- **immission** (metrics and refraction).

This is also formally reflected in the common equation for aircraft noise propagation

$$L_P = L_W + D + A \ . \tag{1}$$

according to [3] where L_P denotes the sound pressure level, L_W the sound power level, D the directivity correction, and A the absorption during propagation.

The above breakdown which is defined analogously to [4] has the advantage that the three components can be encapsulated to a large extent which eases development of the three models independently from each other. This process and the respective current status will be described in more detail in the according following subsections.

3.1 Noise Emission (Aircraft Noise)

The basic principles and current status of the noise emission model used for the approach described in this paper are outlined in detail in [5], [6], and [7], yet only an overview is given in the following.

As also depicted in Fig. 3 The basic approach consists in a reasonable splitting of the overall noise source ‘aircraft’ into the following distinct noise source components

- engine jet (incl. combustion and afterburner)
- engine fan (broadband and discrete-tone)
- undercarriage (nose and main landing gear)
- vertical tail
- foreplane
- leading and trailing edge
- airframe
- stores

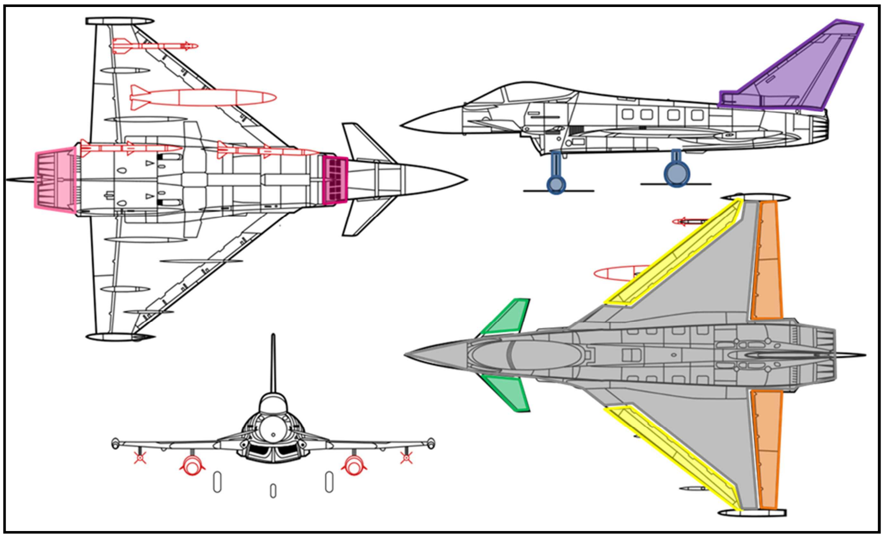


Figure 3 – Aircraft noise emission components.

For each of these noise sources a dedicated noise emission model as well as a respective directivity correction has to be provided. As shown in a subsequent section also the noise propagation is modelled separately for the several sources. Therefore combination of the noise components is not performed until impact at observer point.

Engine noise is modelled using analytical formulas for jet, combustion, afterburner, and fan (e.g. provided in [4]) and will be subject to according corrections based on the results of validation flight test measurements.

Having modelled the noise emissions itself at the several sources of the engine the second component of the complete emission model consists of the near-field behavior of the noise i.e. the directivity corrections for all sources.

It is well known that fan and jet noise emissions (at least vertically) do not show a homogenous expansion. Analogously a similar phenomenon also is expected horizontally especially in the case of a twin engine aircraft with two parallel engines mutually influencing the exhaust airflow. It is therefore essential to consider a three-dimensional directivity correction.

For the synthesis of these corrections however no straightforward analytical approach exists, thus inducing the need for modelling respective directivity functions partly based on heuristics and dedicated tests, i.e. noise measurements.

For all other components (except leading edge) noise emission is modelled as surface noise by some equation of the form

$$p_{component} = C_{component} \cdot \overline{q} \cdot Ma \cdot \frac{\sqrt{A}}{r_{ref}} \cdot F(St) \; . \tag{2}$$

Where C is a component specific constant, $\overline{q}$ the dynamic pressure, Ma the Mach number, A and r_{ref} reference area and length, and $F(St)$ a function based on the Strouhal number. With respect to directivity all these noise emission components are assumed to be approximately monopoles therefore no directivity correction has to be applied.

3.2 Noise Transmission (Propagation)

Having modelled the noise emitted in the near-field of the aircraft the proximate task consists of specifying the propagation to (an observer on) the ground. As described in [8] a simplified (linearized) Ray Tracing method has been established to be of sufficient accuracy in this case and subsequently implemented. Based on the principles of geometric acoustics the method developed here mainly introduces the aspect of the time dependency to noise propagation.

A general characteristic of noise (or more generally sound) propagation through the atmosphere is the phenomenon of attenuation (or absorption) as also contained in Eq. 1. Usually the following three different types of absorption are distinguished.

- **geometric** (radially expanding the sound power is distributed over an area increasing with distance from the source and therefore the sound power per area unit decreases proportionally to the square of the distance)
- **atmospheric** (reduction of the sound intensity due to molecular air absorption)
- **ground** (additional sound attenuation for observer location with an aircraft-ground angle lower than 15°, i.e. mainly applicable for airfield operation or very low flight altitudes)

Transmission phase ends with sound impact at the observer as described in the following subsection.

3.3 Noise Immission (Observer Perception)

As it can be seen e.g. in Eq. 1 for the characterisation and measurement of the noise perceived by an observer on ground the so called sound pressure level L_P is crucial in contrast to the sound power level L_W which describes the noise emitted by the aircraft. Accordingly for noise impacting on ground the most important effects are

- **ground absorption** (as described in the preceding subsection)
- **reflection** (of utmost importance especially in the case of the airfield and observer being in the vicinity of mountains, e.g. Switzerland, or in an area with many buildings around)
- **bending** (deflection due to obstacles)

The latter two effects are currently not modelled but will be taken into account in future program versions. Furthermore the current model of the ground as planar surface will then be replaced by a proper ground modelling based on a terrain database. Refined modelling up to a level of detail also containing buildings is currently not planned.

4 Validation Approach

As already indicated above with respect to modelling distinct approaches for engine and non-engine noise emission components have been chosen. Accordingly this strategy also has been pursued for validation. Nevertheless despite this distinction all models share the fact that they originally are based on textbook formulas. Moreover the dedicated validation flight tests described below were also aiming at substantiation or refinement (where applicable) of all noise emission models. There is however some additional information from tests performed in the past that also can be used selectively for noise model validation purposes but due to the respective measurement approaches application is limited to engine noise.

Generally engine (fan, combustion, jet) noise validation is performed in a first step by comparison of noise emission data calculated/derived from measured noise data with the according data provided by the correspondent emission model for the respective test conditions. Subsequently matching of the respective two datasets/curves is attempted by fine-tuning of suitable model parameters. In case that after this refinement process there are yet some significant discrepancies it is assumed that these are due to the respective directivity characteristics and therefore are allotted to these directivities which at least for the engine are not modelled analytically but have to be derived from heuristic approaches refined by noise measurement test data as described above.

For non-engine noise emission models the first validation step consists as above of the comparison of noise emission data calculated/derived from measured noise data with the according data provided by the correspondent emission model for the respective test conditions. Potential remaining discrepancies after matching of test and model data however in this case cannot be attributed to directivity characteristics as the non-engine noise emission models are assumed to be monopoles as described above. Therefore in order to achieve a proper match of data/curves for validation the model itself has to be adapted accordingly. The complete process is presented in Fig. 4.

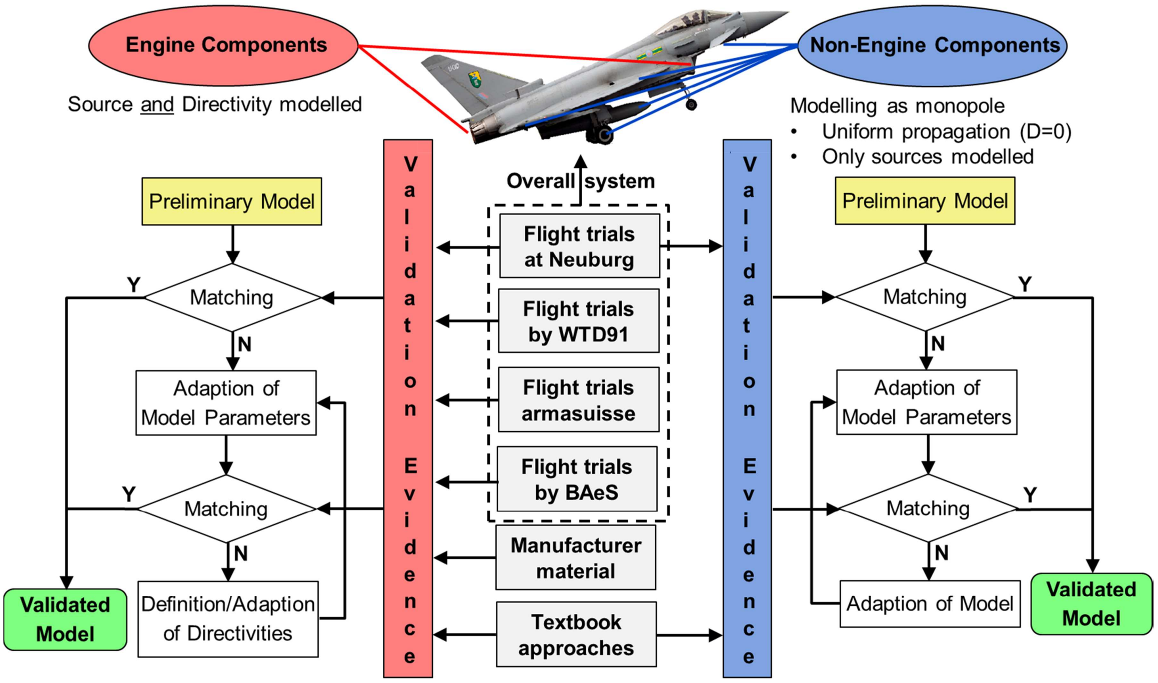
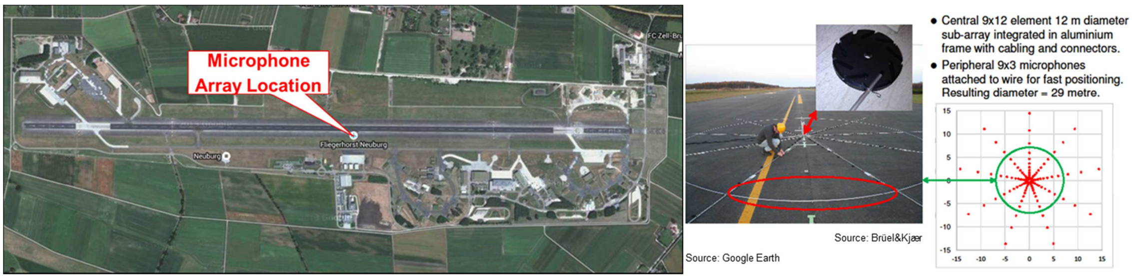


Figure 4 – General noise model validation approach.

The tests performed by WTD91, armasuisse, and BAeS as well as additional engine manufacturer material are exclusively used as additional information for engine noise model validation.

5 Noise Model Validation Flight Tests

As described above for substantiation, refinement, and validation of the noise emission models originally developed on a mainly analytical/textbook basis respective noise measurement flight tests are essential. Accordingly appropriate tests have been performed in November 2015 at Neuburg airfield (Fig. 5) with the support of the Danish company Brüel&Kjær which provided the noise measurement equipment (microphone array, recording hardware, etc.) and as well conducted the noise recording and post processing.



- Central 9x12 element 12 m diameter sub-array integrated in aluminium frame with cabling and connectors.
- Peripheral 9x3 microphones attached to wire for fast positioning. Resulting diameter = 29 metre.

Source: Google Earth

Source: Brüel&Kjær

Figure 5 – Noise measurement setup at Neuburg airfield.

A total of 20 test points (fly-overs) have been performed in different configurations and with varying power settings at altitudes between 150 and 200 ft above airfield as summarised in Tab. 1.

Table 1 – Validation flights.

#	Power Setting	Landing Gear	External Tanks
1	Max Dry	Up	Off
2	Max Reheat	Up	Off
3	Max Dry	Down	Off
4	Max Dry	Up	Off
5	Max Reheat	Up	Off
6	Max Dry	Down	Off
7	Max Dry	Up	Off
8	Max Reheat	Up	Off
9	Max Dry	Down	Off
10	Part Dry	Up	On
11	Max Reheat	Up	On
12	Part Dry	Down	On
13	Part Dry	Up	On
14	Max Reheat	Up	On
15	Part Dry	Down	On
16	Part Dry	Up	On
17	Max Reheat	Up	On
18	Part Dry	Down	On
19	Max Dry	Up	On
20	Max Dry	Down	On

Subsequent to this flight test campaign the recorded noise data have been analysed, evaluated, and processed by Brüel&Kjær for the validation purposes as described in the following section.

6 Flight Test Data Analysis and Processing for Model Validation

After completion of the noise measurement test flight campaign as described above all measured data have been transferred to Brüel&Kjær for analysis. This comprises not only noise data but as well information on respective meteo data (wind direction and speed, temperature, humidity) and flight path information measured by an according FPR pod mounted at the wing tip (Fig. 6).

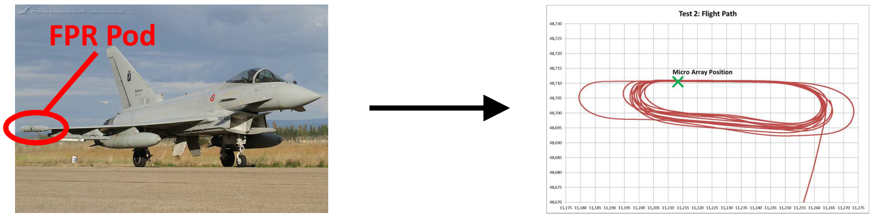


Figure 6 – Flight path recording.

Subsequently all these data from different sources have been consolidated by Brüel&Kjær and a dedicated Beamforming technique [9] has been applied in order to extract the required noise emission data for the different sources. For this purpose at first distinct areas at the aircraft for noise source identification have been defined jointly (Fig. 7).

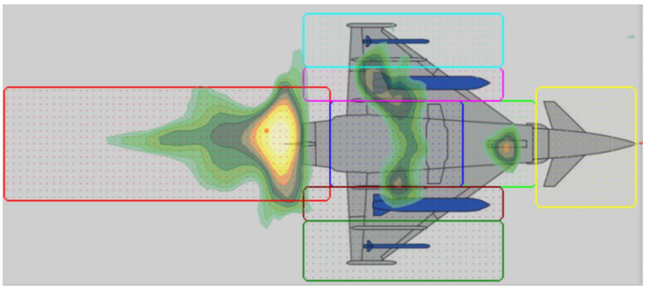


Figure 7 – Sound power areas.

This is then followed by an according analysis of the measured noise immision data by Brüel&Kjær using their dedicatedly developed beamforming system. This consists here mainly of two steps [9]

- **Tracking Delay and Sum (DAS) beamforming** (with averaging in short intervals)
- **Deconvolution** (estimation of amplitude distribution)

This process finally led to the sound power information needed for the different noise sources specified as well as to respective directivity correction/information where applicable (Fig. 8).

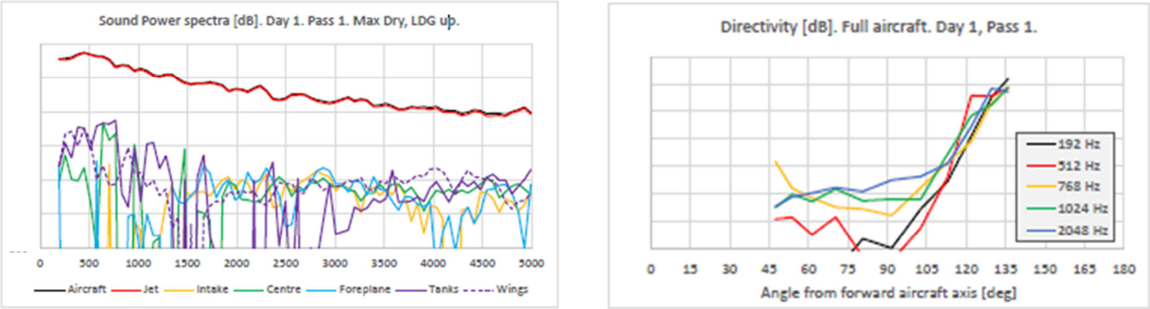


Figure 8 – Example of sound power and directivity characteristics.

With these the results final refinement and validation process for the aircraft noise sources could be started. As already outlined in Fig. 4 using the resulting data described above the parameters of the respective emission models will be adapted iteratively and the model themselves will be refined where necessary. Additionally for the non-monopole models respective directivity characteristics will be defined.

7 Conclusions

A generic approach for noise modelling of high performance military aircraft substantiated by a corresponding validation flight test campaign has been presented. Due to the modular structure of the aircraft noise model each noise source can be modelled and validated separately thus giving way to flexibility with respect to potential introduction of new noise sources (e.g. stores) as well as to application of the basic noise calculation software to different aircraft types. A dedicated validation strategy for this approach has been developed and an according flight test campaign has been performed leading to first promising results. Future planned activities comprise the completion of the overall model refinement and validation, the implementation of a terrain data base, parallelization of the source code (where feasible), and finally the development of dedicated flight path (noise) optimisation program using the aircraft noise model described here.

Acknowledgements

Special thanks go to Brüel&Kjær (especially Mr. Jørgen Hald and Mr. Koichi Imai) for their invaluable efforts and support of the flight test by providing and installing the microphone array as well as measuring, analyzing, and finally providing the noise data. Additionally many thanks go to Mr. Christian Waizman and Mr. Joey Borkenstein for planning and conduction of the test flights, Mr. Matthias Nitsche for PMO support and last but not least Mr. Florian Mayer for his acoustic expertise.

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