ICAS 2016 30th Congress of the International Council of the Aeronautical Sciences DCC, Daejeon, Korea ; September 25-30, 2016

COMPARATIVE EFFICIENCY ANALYSIS OF DISTRIBUTED PROPULSION SYSTEMS FOR PROPULSIVE FUSELAGE AND HYBRID WING BODY CONCEPTS IN FP7 PROJECT "DISPURSAL"

A.Mirzoyan*, A.Isyanov*, A. Isikveren**
***Central Institute of Aviation Motors (CIAM), 111116, Moscow, Russia, **SAFRAN S.A. (Magny Les Hameaux, 78772, France)**

Keywords: *distributed propulsion system, propulsive fuselage, hybrid wing body*

Abstract

The paper discusses results of investigation and analysis of advanced aircraft and propulsion system concepts with distributed propulsion, i.e. unconventional aircraft like Hybrid Wing Body with multiple fans driving by engine cores, as well as aircraft with an auxiliary single fan driven by an engine core installed in the fuselage aft cone (so called propulsive fuselage aircraft concept).

1 Introduction

"DisPURSAL" (Distributed Propulsion and Ultra-high By-Pass Rotor Study at Aircraft Level) is a Level-0 project of 7 European Framework Programme. It is dedicated for investigation and analysis of two advanced commercial aeroplane configuration: unconventional configuration like Hybrid Wing Body (HWB) with Distributed Propulsion System (DPS), including multiple fans, driving by engine cores (Distributed Multiple-Fans Configuration, DMFC), as well as aircraft configuration with an auxiliary unconventional single fan-propulsor driven by a engine core installed in the fuselage aft cone (Propulsive Fuselage Concept, PFC) [1,2].

Bauhaus Luftfahrt e.V. (Germany) was coordinator of the 2-year project. Also CIAM (Russia), ONERA (France) and Airbus Group Innovations (Germany) were involved in the project

Essential feature of the both concepts is Boundary Layers Ingestion (BLI) from the fuselage surface, which reduce the airframe drag, but simultaneously degrade the engine performance. The paper commits to results of comparative analysis of the two concepts efficiencies first of all with respect to fuel consumption and environmental performance (community noise, NOx and CO_2 emissions). Aspects such as design and optimization of concepts, airframe-propulsion integration and design optimization, power-train system design and advanced flow field simulation, and etc. are also considered in the project.

2 Aircraft Top-Level Requirements and reference (base) aeroplanes

Aircraft Top-Level Requirements to main mission and environmental aircraft performances as well as to reference (base) aeroplanes were adopted for comparative studies of aircraft concepts.

2.1 Aircraft Top-Level Requirements

Based on published data given in Ref. [3, 4] it was decided to consider medium-to-long range aeroplanes with passenger capacity 320 – 340 pax. This type of aeroplanes have the greatest contribution in cumulative fuel consumption of aircraft fleet. Also according to the forecasts up to year 2035 about 95% of the passenger operations within this aircraft market segment are performed by the aeroplanes with such passenger capacity.

The rest of the requirements for considered aeroplanes are presented in the Table 1 [2].

Table 1: Aircraft Top-Level Requirements [2]

Entry-into-Service	2030 / 2035
Design range and passenger capacity	4800 nm 340 pax
Design cruise flight Mach number	>0.75
Max cruise flight altitude	FL410
Community noise and emissions goals (Datum year 2000, SRIA 2035)	Noise-55% NO_x-84% CO_2-60%
COC per pax	-20% vs. A330
Takeoff field length	≤ 2300 m
Landing Field Length	≤ 2000 m
Approach Speed	≤ 140 KCAS
Airport Compatibility Limits (ICAO Annex 14)	Code E (52 m < x < 65 m)

2.2 Reference aeroplanes

Two reference aeroplanes are considered as datum at aeroplanes comparative analysis: State-of-the Art aeroplane like A330-300 with engines like Trent 700, reflecting in-service year 2000 (SoAR aeroplane, Fig. 1) [1,2] and advanced aeroplane of conventional tube and wing configuration equipped by advanced geared turbofan (GTF) with high BPR and target EIS of 2035 (2035R aeroplane, Fig. 2) [1,2].

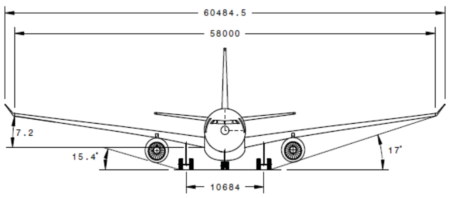

Fig.1. SoAR reference aeroplane.

Fig. 2. 2035R reference aeroplane.

According to the investigations the fuel efficiency of 2035R reference aeroplane is higher than one of SoAR reference aeroplane by 32%.

3 Comparative efficiency of concepts on fuel consumption and CO_2 emission criteria

3.1 Results of preliminary down-selection framework

Following 2 basic configurations were chosen as results of preliminary down-selection process of most promising concepts: configuration of Hybrid Wing Body (HWB) with embedded DPS for DMFC aeroplane (Fig. 3) and configuration with a single fan driven by a gas-turbine installed in the fuselage aft cone for PFC aeroplane (Fig. 4).

Fig. 3. Down-selected DMFC aeroplane configuration [2].

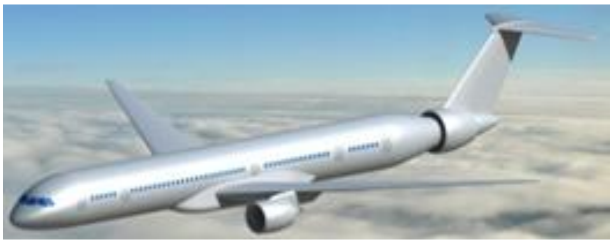

Fig. 4. Down-selected PFC aeroplane configuration [2].

DPS of down selected DMFC configuration consists of 2 turbofan and 4 mechanical driven remote fans.

In order to provide meeting of transport category certification requirements at main propulsors failure, the down selected PFC aeroplane configuration additionally comprises two under-wing podded ultra-high BPR turbofans.

3.2 Results of fuel efficiency assessments

Mission performance of SoAR, 2035R, DMFC and PFC aeroplanes are compared in the Table 2. Regarding design mass, the 2035R aeroplane indicates a reduction of 9.9% in Maximum Take-Off Mass (MTOM) due to installation of very high BPR GTF propulsion system (PS) and use of more spacious cabin [2].

Table 2: Comparative mission performance of considered aeroplanes

	Unit	SoAR	2035R	DMFC	Δ SoAR, %	Δ 2035R, %	PFC	Δ SoAR, %	Δ 2035R, %
Design range	**nm**	4800	4800	4800	-	-	4800	-	-
Passenger capacity	**pax**	340	340	340	-	-	340	-	-
Max Takeoff Mass MTOM	**t**	229.0	206.27	206.54	-9.81	0.13	208.97	-8.75	1.31
Operating Empty Weight OEW	**t**	123.64	123.46	127.24	2.91	3.06	130.59	5.62	5.77
OEW/MTOM	**-**	0.54	0.599	0.616	14.07	2.84	0.625	15.74	4.34
Reference wing area	**kg**	363.1	335.4	614	69.10	83.06	339.8	-6.42	1.31
Wing aspect ratio	**-**	9.3	12.6	6.9	-25.81	-45.24	12.4	33.33	-1.59
Wing span	**m**	58	65	65	12.07	0.00	65	12.07	0.00
Fuselage length	**m**	63.7	67	37	-41.92	-44.78	69	8.32	2.99
Wing loading	**kg/m^2**	630.7	615	336	-46.73	-45.37	615	-2.49	0.00
Total Max Static Thrust	**kN**	632.6	627.2	603	-4.68	-3.86	635.4	0.44	1.31
Thrust loading	**-**	0.282	0.31	0.298	5.67	-3.87	0.31	9.93	0.00
Takeoff field length	**m**	2346	2225	2300	-1.96	3.37	2300	-1.96	3.37
Approach speed	**KCAS**	131	133	140	6.87	5.26	138	5.34	3.76
Ingested Drag Ratio	**%**	n/a	n/a	10.5	-	-	23.7	-	-
Cruise L/D	**-**	20.7	22.5	26.5	28.02	17.78	30.2	45.89	34.22
Total cruise SFC	**g/kN.s**	16.2	13.1	14.5	-10.49	10.69	15.7	-3.09	19.85
Cruise Mach number	**-**	0.80	0.80	0.80			0.80		
Design Payload	**t**	34.68	34.68	34.68			34.68		
Block Fuel @ Max pax and range of 4800 nm	**t**	62.17	42.26	38.96	-37.33	-7.80	38.38	-38.26	-9.17

The DMFC aeroplane has an almost parity in terms of MTOM with the 2035R aeroplane, but with a small penalty of 3.1% of OEW due to the installation of the distributed multiple-fans PS.

The PFC aeroplane is worse 2035R aeroplane by 1.3% on MTOM and by 6% on OEW due to installation of single propulsors in the fuselage aft cone.

The higher OEW/MTOW ratio of 2035R, DMFC and PFC aeroplanes in relation to the SoAR aeroplane indicate the significant reduction of their fuel consumption providing compliance of same transportation problem (transportation of 340 pax on design range of 4800 nm).

As expected, DMFC aeroplane with HWB configuration has a low wing loading and wing aspect ratio even taking into account wing span limitation according to ICAO Annex 14 Code E [5].

3.3 Results of environmental performance assessments

The restrictions on community noise, NOx and CO_2 emissions are directly defined by ICAO International Standards, described in Annex 16, Volume I "Aircraft noise"[6], Volume II "Aircraft engine emissions"[7] and Volume III "Aircraft CO_2 emission"[8].

3.3.1 Comparison of community noise levels

The Cumulative noise level (CNL) is defined as the arithmetic sum of the noise levels at each of three certification points. According to ICAO Noise Standards noise certification level of new aeroplane should meet following requirements:

- allowable noise levels depends on aircraft MTOM (Fig. 5) [9];

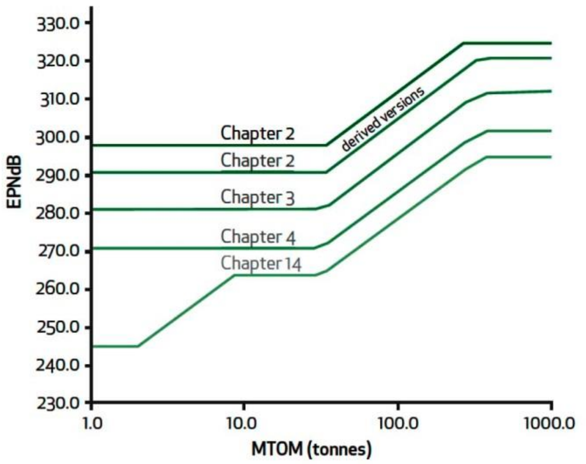

Fig. 5. Different noise certification limits of ICAO Noise Standards depending on MTOM [9].

- CNL should meet requirements of new Chapter 14 of ICAO Annex 16, Vol. I [6] and should has margin greater than 17 EPNdB relative to Chapter 3 (it is applied for new type aeroplanes with MTOM higher than 55 tons since 2017, and for new type aeroplanes with MTOM less or equal 55 tons since 2020);
- Chapter 3 limits must be met in all noise certification points;
- Tradeoff on noise level in a certification point using other margins is not allowed;
- The sum of any two margins relative to Chapter 14 must be greater than 2 EPNdB.

Due to lack of information expert evaluation of predicted CNL for considered aeroplanes was carried out in the work. Some additional quantitative assessments of fan, jet and airframe noise taking into account liners efficiency were performed by CIAM in-house programs. Shielding effect by airframe surface for DMFC was estimated based upon publications made by NASA [10], ICAO [11], and various CIAM internal reports. According to the ICAO Independent Experts Report [11] uncertainties of noise predictions of advanced aeroplane configurations strongly depend upon morphology type and EIS.

Majority features of the advanced aircraft morphology such as using novel acoustic liners, ultra-high BPR engines, additional gearbox noise sources and noise shielding effect taken into account in the assessment of the CNL of aircraft concepts 2035R, DMFC and PFC. The CNL of the SoAR aircraft with Trent 700 engine corresponds to certification data from NoiseDB database [12].

Results of assessments of nominal CNL values and their uncertainties are presented on the Fig. 6.

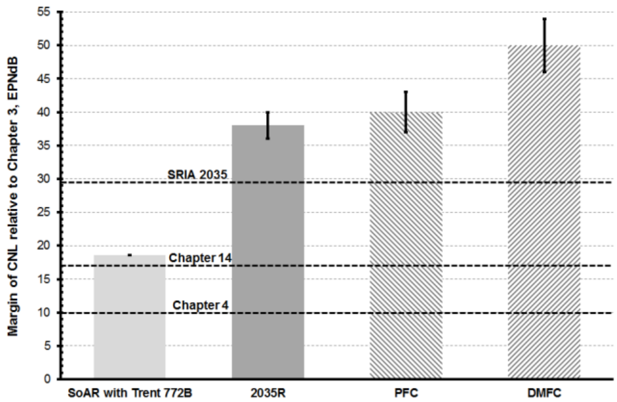

Fig. 6. Results of community noise prediction for SoAR, 2035R, DMFC and PFC aeroplanes.

It can be seen that 2035R and PFC aeroplanes meet adopted noise requirements (on the plot they corresponds SRIA 2035 requirements). DMFC aeroplane has significantly higher noise margin (approximately 10 ENPdB) in comparison with PFC aeroplane due to noise shielding by HWB surface. Nevertheless it should be taken into account that uncertainty of noise prediction of the aeroplane is maximal (about ±4 EPNdB) due to lack of experimental information on shielding effect efficiency for configurations like HWB.

3.3.2 Comparison of NOx emission levels

In order to improve the environmental conditions around airports ICAO regularly declare more stringent emissions (NOx, unburnt hydrocarbons, carbon monoxide and smoke) standards [6]. Since 2008 ICAO Standard on NOx emission (CAEP/6) was enforced, and it is more stringent than NOx Standard 1996 (CAEP/2) by ~30% and more stringent than NOx Standard 2004 (CAEP/4) by ~12%.

In 2010 ICAO trough the Committee on Aviation Environmental Protection (CAEP) accepted new requirements to NOx emission (CAEP/8). The main requirements provide following:

- since 2013 to cut-off production of engines unsatisfying CAEP/6 (ICAO 2008, Tier 6) emission requirements;
- since 2014 to make more stringent the certified NOx emission level relating to ICAO 2008 by 5…15% for engines with thrust of 26.7…89.0 kN and by 15% for engines with thrust higher than 89.0 kN and engine Overall Pressure Ratio (OPR) higher that 30 (CAEP/8, Tier 8).

Besides CAEP confirms predicted level of NOx reduction for engines with OPR = 30 relative to CAE/6 level by 40% in 2016, and by 60% in 2026.

According to "DisPURSAL" requirements the 2035 goal of NOx emissions reduction is 84% reduction relative to 2000 typical level. It means using radical new technologies alongside improved low NOx combustion, higher engine efficiency, whole air vehicle weight reduction, and optimized flight operations. The 2035 SRIA NOx goal for local air quality is a 65% reduction margin from CAEP/6 [6].

PS of PFC aeroplane includes 2 type of engines: 2 podded engines and 1 rear engine with fuselage fan. As podded and rear engines have different OPR, mean value of OPR was also defined. Main results of NOx emission assessment for PSs of considered aeroplanes are presented on the Fig. 7. Mean values of OPR for PS of PFC aeroplane are presented on the Fig. 7 by dashed line. ICAO Standards did not take in account PS with 2 different type of engine with different OPR and calculation of ICAO Standard level for the case is a problem.

As it can be seen, podded engines of PFC aeroplane and DMFC aeroplane engine have margin to SRIA 2035 level on NOx emission levels 10-22%. PS of SoAR aeroplane and rear engine of PFC aeroplane fail SRIA 2035 requirements by 75%. NOx emission level of rear engine of PFC aeroplane is so high due to worse SFC, connecting with BLI, and low thrust level of the rear engine. But NOx emission level for whole PS of PFC aeroplane is close to SRIA 2035 requirement (see Fig. 7).

3.3.3 Comparison of CO_2 emission levels

According to certification procedure, described in ref. [7], the value of CO_2 emission level CO2EEM is CO_2 metric, limited by new ICAO CO_2 Standard:

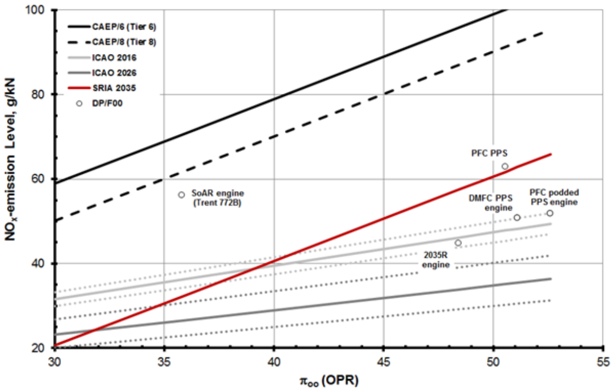

Fig. 7. Results of NOx emission prediction for SoAR, 2035R, DMFC and PFC aeroplanes.

$$CO2EEM = (1/SAR)_{AVG}/RGF^{0.24}, \quad (1)$$

where

SAR is Specific Air Range, reciprocal value of cruise fuel consumption per 1 km of range;

$(1/SAR)_{AVG}$ is mean value of 1/SAR, calculated in 3 cruise flight points at 3 cruise Gross Weights (GW): high GW GW1 = 0.92*MTOM, low GW GW2 = (0.45 *MTOM) + (0.63 * ($MTOM^{0.924}$)), mean GW GW3 = (GW1+GW2)/2;

RGF is Reference Geometric Factor;

MTOM is certified Max Takeoff Mass in kilograms.

RGF value characterizes fuselage size and indirectly defines maximum passenger capacity of commercial aeroplanes or maximum payload of cargo aeroplanes.

For aeroplanes with a single deck RGF is determined by the area of a surface (expressed in m^2) bounded by the maximum width of the fuselage outer mould line (OML) projected to a flat plane parallel with the main deck floor.

For aeroplanes with an upper deck RGF is determined by the sum of the area of a surface (expressed in m^2) bounded by the maximum width of the fuselage OML projected to a flat plane parallel with the main deck floor, and the area of a surface bounded by the maximum width of the fuselage OML at or above the upper deck floor projected to a flat plane parallel with the upper deck floor (Fig.8).

RGF value initially measuring in m^2 then is converted in non-dimensional form by dividing by 1 m^2.

The RGF includes all pressurized space on the main or upper deck including aisles, assist spaces, passage ways, stairwells and areas that can accept cargo and auxiliary fuel containers. It does not include permanent integrated fuel tanks within the cabin or any unpressurized fairings, nor crew rest/work areas or cargo areas that are not on the main or upper deck (e.g. 'loft' or under floor areas). RGF does not include the cockpit crew zone. The aft boundary to be used for calculating RGF is the aft pressure bulkhead. The forward boundary is the forward pressure bulkhead except for the cockpit crew zone. Areas that are accessible to both crew and passengers are excluded from the definition of the cockpit crew zone. For aeroplanes with a cockpit door, the aft boundary of the cockpit crew zone is the plane of the cockpit door. For aeroplanes having optional interior configurations that include different locations of the cockpit door, or no cockpit door, the boundary shall be determined by the configuration that provides the smallest cockpit crew zone. For aeroplanes certified for single-pilot operation, the cockpit crew zone shall extend half the width of the cockpit. Fig. 8 is obviously explains how RGF value is defined [8].

The results of comparative assessment of CO2EEM relative values for all considered aeroplanes (SoAR aeroplane is considered as a datum) are presented in the Table 3. It could be noted that CO_2 emission of SoAR aeroplane is higher by 40-42% than rest aeroplanes due to worse aerodynamic efficiency and low fuel consumption of Trent 700 engines.

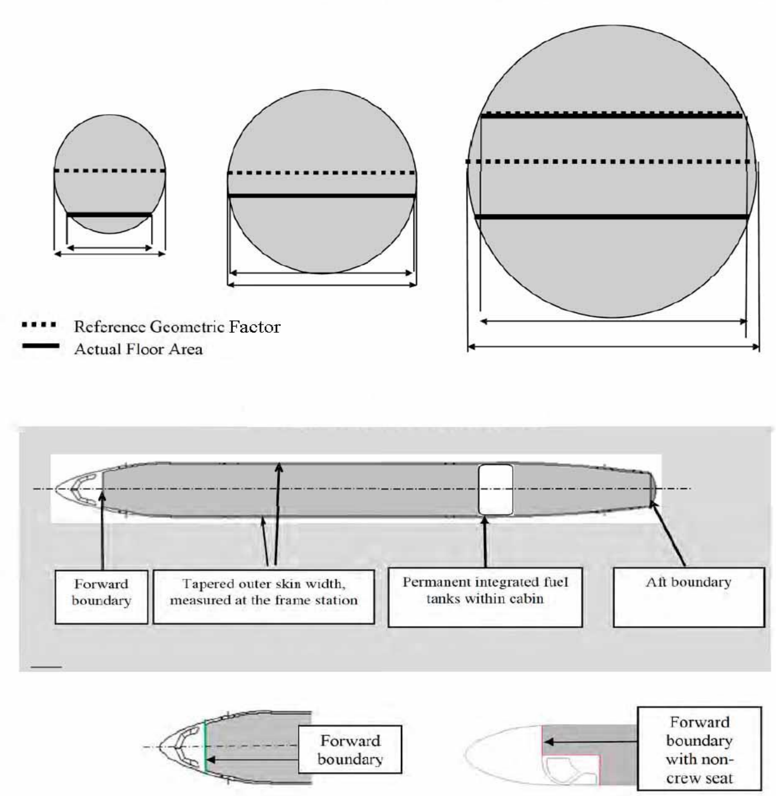

Fig. 8. Cross-sectional and longitudinal views for clarification of RGF value definition.

Table 3. Results of CO_2 emission assessment.

	Unit	SoAR	2035R	DMFC	PFC
MTOM	**kg**	229 000	206 270	206 540	208 980
GW1	**kg**	210 696	189 766	190 017	192 251
GW2	**kg**	159 533	144 091	144 277	145 927
GW3	**kg**	185 114	166 929	167 147	169 089
RGF	**m^2**	294.0	333.9	293.0	333.9
SAR_{AVG}	**km/kg**	0.1547	0.2608	0.2598	0.2608
CO2EEM	**kg/km**	1.652	0.951	0.954	0.981
ΔCO2EEM	**%**	0	-42.4	-42.3	-40.6

Margins on CO2EEM level relative to potential ICAO regulatory level for New Type aeroplanes (applicable for 2035R, DMFC and PFC aeroplanes) and In-Production aeroplane (applicable for SoAR aeroplane) are presented on Fig. 9.

It is seen that SoAR reference aeroplane practically has not margin, and in the same time 2035R, DMFC and PFC advanced aeroplanes could provide margins higher than 30%.

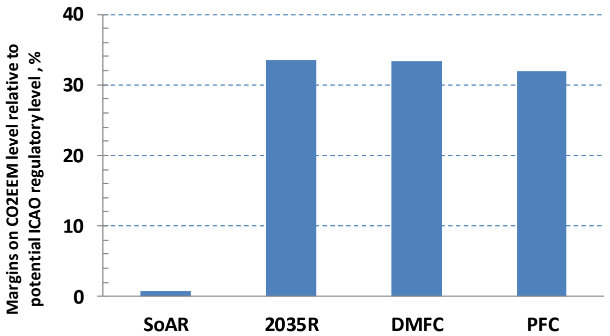

Fig. 9. Relative margins of CO2EEM relative ICAO potential regulatory levels.

4 Conclusions

The paper presents the results of comparative investigations and analysis of 2 advanced aeroplane concepts with DPS. DMFC with multi-fans mechanically driven by several engine cores and RFC with single fan driven by an engine core installed in the fuselage aft cone are considered as primary concepts.

It was assumed that 2035 would be entry-in-service time for both concepts.

The investigations showed:

- For a design range of 4800 nm with 340 passengers at M0.80 cruise speed, block fuel burn reduction compared to conventional reference aeroplane 2035R was predicted to be 7.8% (for DMFC aeroplane) and 9.2% (for PFC aeroplane). Relative to SoAR reference aeroplane the reduction of block fuel consumption could account 37.3% and 38.3% accordingly;
- There appears to be a good likelihood of meeting the SRIA 2035 community noise and NOx emissions targets by DMFC and PFC aeroplanes;
- Using methods currently being considered by ICAO for upcoming issuance of Annex 16, Volume III, 40-42% lower CO_2 emission levels for DMFC and PFC aeroplanes versus the SoAR aeroplane are predicted.

5 Acknowledgments

Authors express their gratitude to the following individuals for their contributions to the analysis and work presented in this paper:

- Olivier Altinault, ONERA
- Julian Bijewitz, Bauhaus Luftfahrt
- Gerald Carrier, ONERA
- Jan-Luck Godard, ONERA
- Richard Grenon, ONERA
- Sascha Kaiser, Bauhaus Luftfahrt
- Mario Kalanja, AGI
- Stephan Stuckle, AGI
- Kay Plötner, Bauhaus Luftfahrt
- Clément Pornet, Bauhaus Luftfahrt
- Alexander Prendinger, undergraduate
- student Bauhaus Luftfahrt
- Michael Schmidt, Bauhaus Luftfahrt
- Arne Seitz, Bauhaus Luftfahrt
- Patrick Vratny, Bauhaus Luftfahrt

References

[1] Isikveren, A.T., Seitz, A., Bijewitz, Hornung, M., Mirzoyan, A., Isyanov, A., Godard, J.-L., Stückl, S., van Toor, J. Recent Advances in Airframe-Propulsion Concepts with Distributed Propulsion, ICAS2014-1.7.3, St. Petersburg, Russia, 2014

[2] Isikveren, A.T., Seitz, A., Bijewitz, J., Mirzoyan, A., Isyanov, A., Godard, J.-L., Stückl, S. Distributed Propulsion and Ultra-high By-Pass Rotor Study at Aircraft Level. Aeronautical Journal, Vol.119, issue 1221, November 2015, pp. 1327-1372.
[3] AERO2k. Global Aviation Emissions Inventories for 2002 and 2025, website: http://aero-net.info/fileadmin/aeronet_files/links/documents/AERO2K_Global_Aviation_Emissions_Inventories_for_2002_and_2025.pdf , cited June 2013.
[4] Official Airline Guide (OAG) Historical Data, 2012.
[5] International Civil Aviation Organization (ICAO) ICAO Annex 14 to the Convention on International Civil Aviation Aerodromes, Volume 1, Aerodrome Design and Operations, 4th Edition, July 2004.
[6] International Civil Aviation Organization (ICAO) ICAO Annex 16 Environmental Protection Vol.I Aircraft Noise , 6th ed., 2011.
[7] International Civil Aviation Organization (ICAO) ICAO Annex 16 Environmental Protection Vol.II Aircraft Engine Emission, 3rd ed., 2008.
[8] CAEP/9-agreed certification requirement for the Aeroplane CO_2 Emissions Standard: ICAO Cir 337. 2013.
[9] Dickson N., Aircraft Noise Technology and International Noise Standards. www.icao.int/SAM/Documents/2014-ENV/ 3.2.Noise%20TechnologyV3_notes.pdf
[10] Bradley, M., Droney, C., Paisley, D., Roth, B., Gowda, S., Kirby, M. NASA N+3 Subsonic Ultra Green Aircraft Research. SUGAR, Final Review, April 2010.
[11] Mongeau, L. Noise Technology Goals, Summary of the conclusions of the second CAEP Noise Technology Independent Expert Panel (IEP2), ICAO Symposium on aviation and climate change, “Destination Green”, May 2013.
[12] Noise Certification Database NoisedB, http://www.noisedb.stac.aviation-civile.gouv.fr , accessed December 2014.

Copyright Statement