TURBOELECTRIC DISTRIBUTED PROPULSION MODELLING ACCOUNTING FOR FAN BOUNDARY LAYER INGESTION AND INLET DISTORTION

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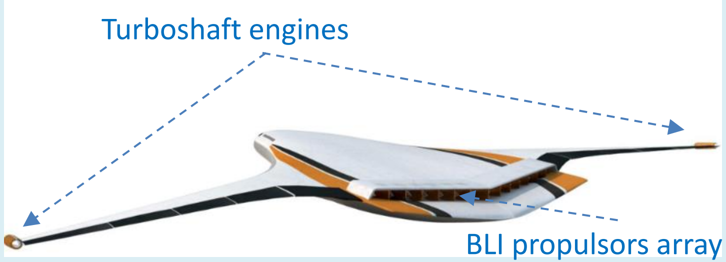
Scope of Paper

- Development of a modelling approach for **BLI** (**B**oundary **L**ayer **I**ngestion) propulsion systems
- Consideration of the inlet distortion distribution alongside the propulsors
- Quantification of BLI effect on propulsion system performance

Study of this Paper

- **N3-X Aircraft concept**[1]
  - Hybrid Wing Body aircraft
  - **T**urbo**e**lectric **D**istributed **P**ropulsion (**TeDP**)
  - BLI Propulsors



- Boundary Layer Ingesting airflow
  1. Reduces inlet momentum drag
  2. Reduced aircraft net drag
  3. Increases propulsor inlet distortion

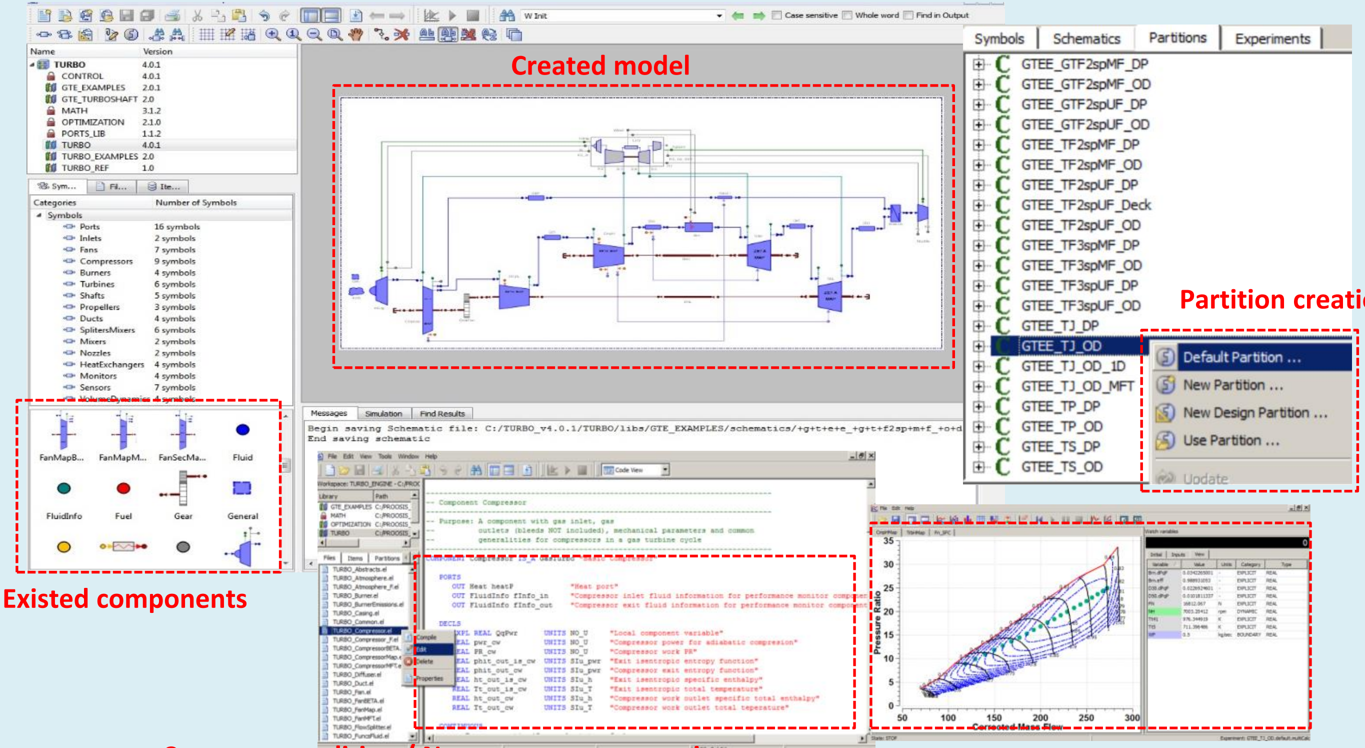
- BLI gains in TeDP system performance
  1. Lower power requirements compared to a equivalent propulsion system of podded propulsors
  2. Reduced fuel burn (up to 10% lower TSFC[1,2,3,4])
  3. Increased propulsive efficiency (≤5%[1])

[1]Felder, J. L., Kim, H. D. and Brown, G. V., "An Examination of the Effect of Boundary Layer Ingestion on Turboelectric Distributed Propulsion", 49th AIAA Aerospace Science meeting, 2011.
[2]A. Turnbull, H. Jouan, P. Giannakakis, A. T. Isikveren, "Modelling Boundary Layer Ingestion at the Conceptual Level", Department of Energy and Propulsion, SAFRAN S.A., ISABE-2017-22700, 2017.
[3]R. T. Kawai, D. M. Friedman, L. Serrano, "Blended Wing Body (BWB) Boundary Layer Ingestion (BLI) Inlet Configuration and System Studies", NASA/CR-2006-214534, December, 2006.
[4]J. R. Welstead, J.L. Felder, "Conceptual Design of a Single-Aisle Turboelectric Commercial Transport with Fuselage Boundary Layer Ingestion", 54th AIAA Aerospace meeting, AIAA-2016-1027, 2016.

Modelling Tool

PROOSIS (PRopulsion Object-Oriented SImulation Software)[14]

- **Object-Oriented**
- **Steady State**
- Transient
- Multi-Disciplinary
- Multi-Point Design
- **Off-Design**
- Test Analysis
- Diagnostics
- Sensitivity
- Optimization
- Deck Generation



[14]A. Alexiou, Introduction to Gas Turbine Modelling with PROOSIS, Madrid, Spain: Empresarios Agrupados Internacional (E.A.I.) S.A., 2014.

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2. Different Propulsors Array Location

Summary & Conclusions

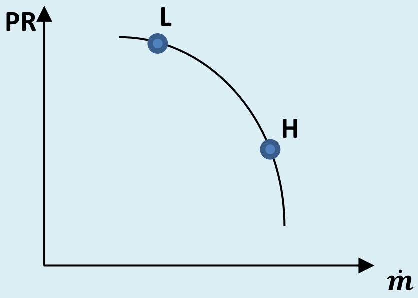
Compressor Inlet Distortion Modelling

Parallel **C**ompressor **T**heory (**PCT**)[15] is utilized to assess the compressor performance under the influence of inlet distortion.

- Circumferentially inlet distorted flow is described by two parallel uniform streams :
  - the **clean stream (H)** of high total pressure and velocity (P_{tH} & V_H)
  - the **distorted stream (L)** of low total pressure and velocity (P_{tL} & V_L)
  - the inlet total temperature is considered uniform
  - each sector extents proportionally to its respective pressure section of distorted inlet
- Each stream enters its own subcompressor → Inlet area is divided into two different virtual segments ($A_{H,in}$ & $A_{L,in}$)

Subcompressors

- Their maps are scaled in terms of mass flow proportionally to their inlet extent
- No scaling is made in terms of pressure ratio and efficiency compared to original compressor map
- Work in parallel at the same rotational speed → operating points of the two subcompressors in the same speed line
- Basic assumptions :
  1. Constant axial velocity through each subcompressor
  2. Common ratio of mass flow rate to inlet area for the two subcompressors



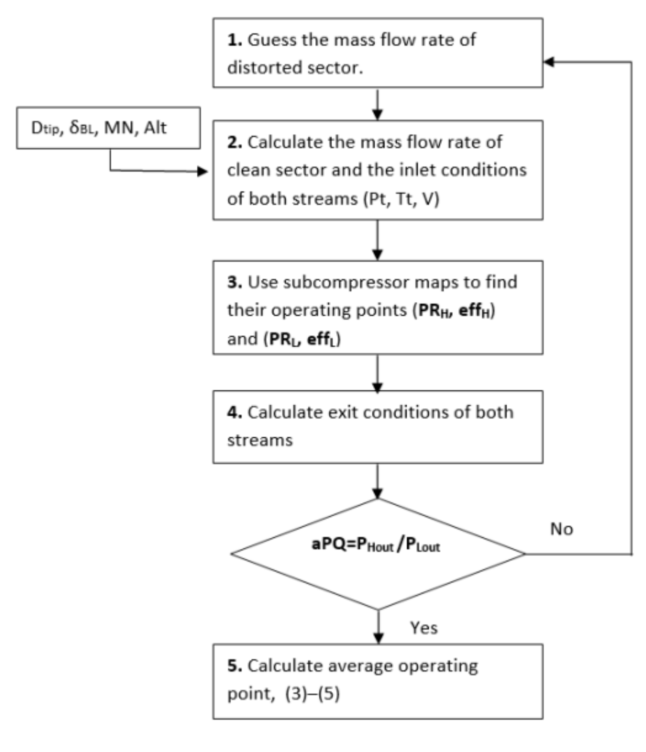
[15]Pearson, H., McKenzie, A. B., "Wakes in Axial Compressors", Journal of the Royal Aeronautical Society, 63, July 1959.

Compressor Inlet Distortion Modelling

- The operating point of overall compressor is calculated as an area-averaged point by adjusting the ratio of exit static pressures of two streams[16]
- The streams are assumed well-mixed providing a uniform flow at compressor exit

Algorithm of calculation procedure

- **Input :**
  - Inlet distortion characteristics (extent and intensity)
  - Inlet geometry (D_{tip})
  - Original compressor map (without presence of distortion)
- **Output :**
  - Exit conditions (P_t, T_t, P_s, T_s, $\dot{m}$, V)

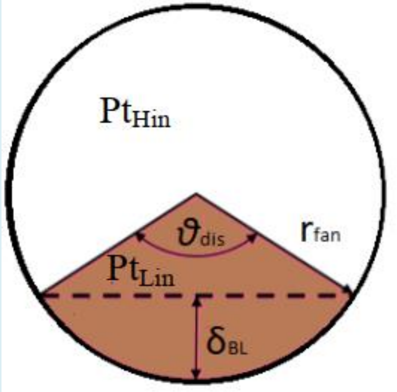


[16]Pokhrel, M., Gladin, J., Garcia, E., Mavris, N., "A Methodology for Quantifying Distortion Impacts using a Modified Parallel Compressor Theory", Proceedings of ASME Turbo Expo 2018, Oslo, Norway, GT 2018-77089, 2018.

BLI Propulsor Model

Propulsor Inlet and Fan Components

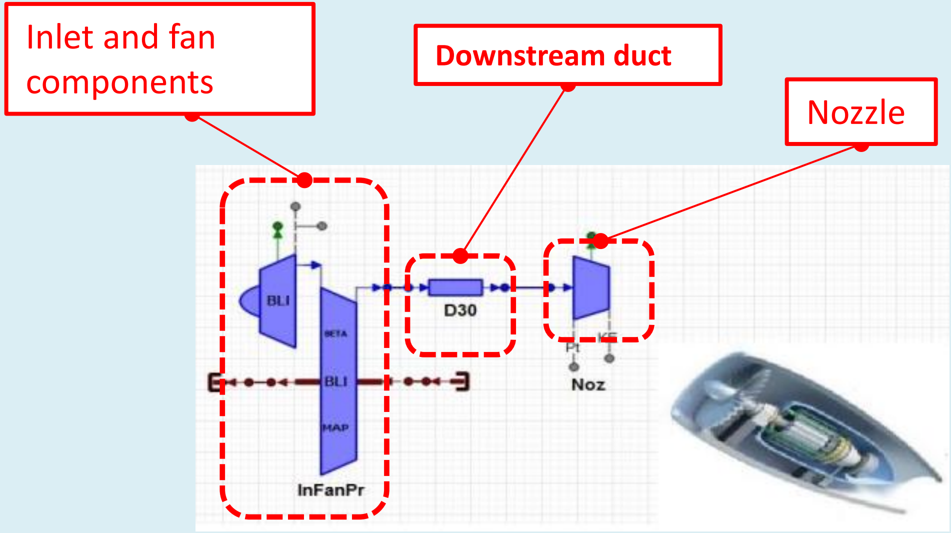
- Treatment of a rectangular-to-circular inlet duct for the propulsor[18]
- Constant P_s, T_t and δ_{BL} through inlet duct
- Boundary layer velocity distribution is estimated with 1/7 power law profile[20]
- Velocity distribution profile is used to assess **H, F_{drag}, D_{tip}**
- Inlet non-uniformity is described as circumferential distortion at fan face
- Inlet distorted fan performance is assessed utilizing PCT
- Fan design adiabatic efficiency and corrected tip speed = f(FPR)[1]
- $W_p = f(D_{tip}, U_{tip})$[20]
    - Only fan and downstream duct are considered for W_p



[18]Hardin, L. W., Tillman, G., Sharma, O.P., Berton, J., Arend, D.J., "Aircraft Study of Boundary Layer Ingesting Propulsion", 48th AIAA/ASME/SAE/ASEE, August 2012.
[20]C. Liu, Turboelectric Distributed Propulsion System Modelling, PhD Thesis, Cranfield University, 2013.
[1]Felder, J. L., Kim, H. D. and Brown, G. V., "An Examination of the Effect of Boundary Layer Ingestion on Turboelectric Distributed Propulsion", 49th AIAA Aerospace Science meeting, 2011.

BLI Propulsor Model

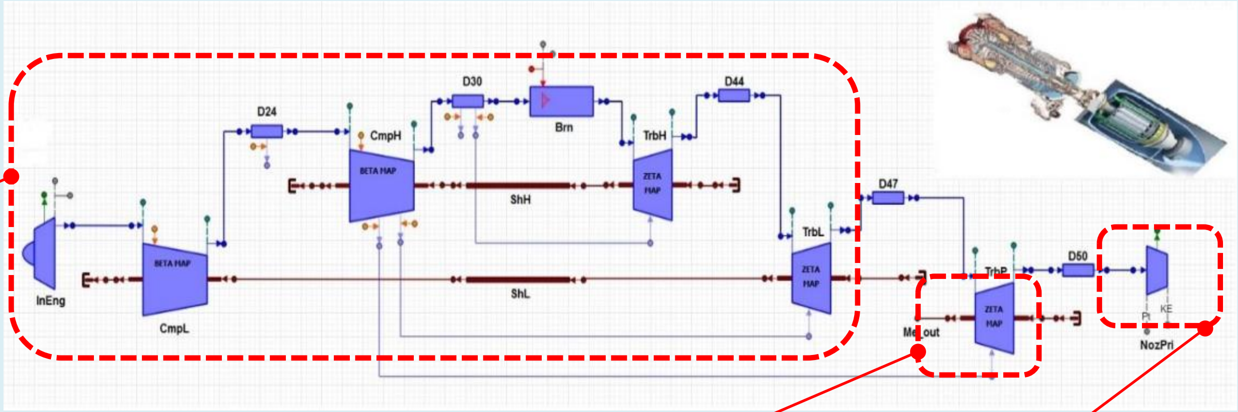
- **Downstream Duct Input :**
  - Pressure drop
- **Nozzle Input :**
  - Thrust and discharge coefficients
  - Nozzle exit area (A_{exit})
- **BLI Propulsor Model Input:**
  - MN, Alt, δ_{BL}
  - Propulsor Geometry (B, D_{tip}, A_{exit})



Turboelectric Distributed Propulsion Model

Turboshaft Engine Model

- Each turbomachinery component utilizes an appropriate map for performance assessment
- **Input**:
  - Components Data (MN, Alt, pressure losses of ducts, A_{exit}, turbomachinery maps)
  - Fuel-to-air ratio
  - Power turbine rotational speed



Turboelectric Distributed Propulsion Model

BLI TeDP Model

- Turboshaft engine model
- Electrical Bus Component
- BLI Propulsor Models
- Half propulsion system configuration is considered (1 turboshaft engine and 7 propulsors)

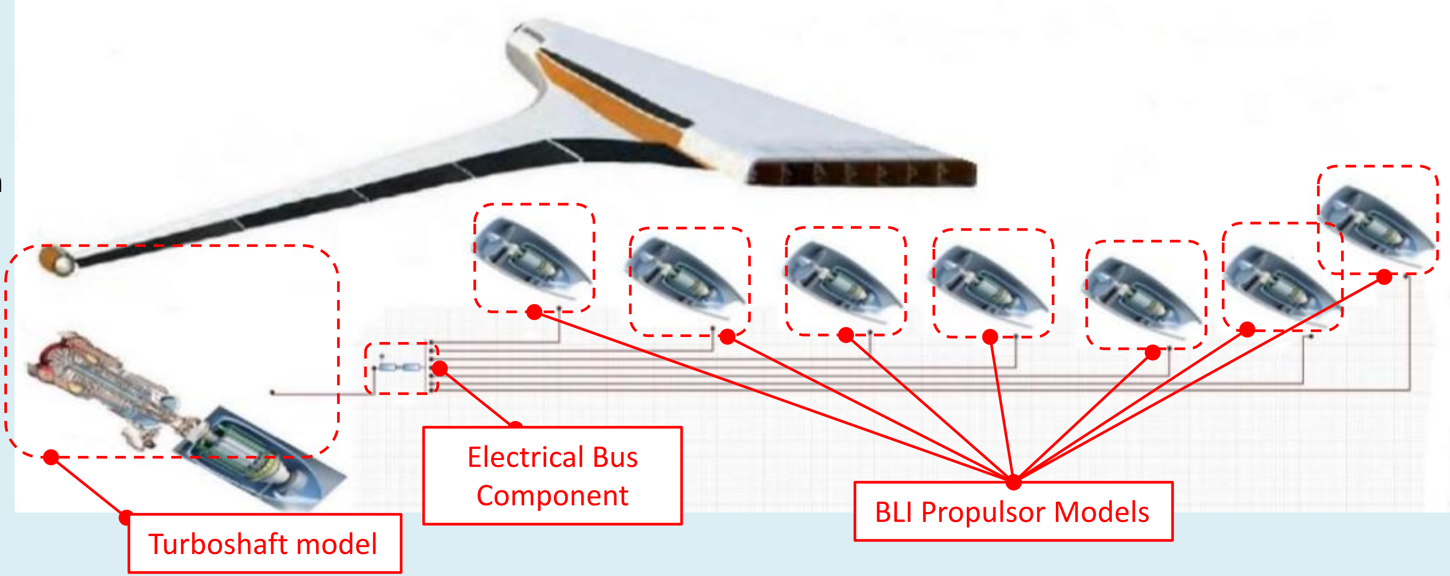
Electrical Bus Component

- Electrical Power transmission (~0.1% power losses)
- Power split between propulsors for common thrust production

Input :

- Flight MN, Alt
- Components Data
- MN & δ_{BL} distribution along propulsors array

Capable of performing calculations for both BLI and non BLI TeDP system configurations

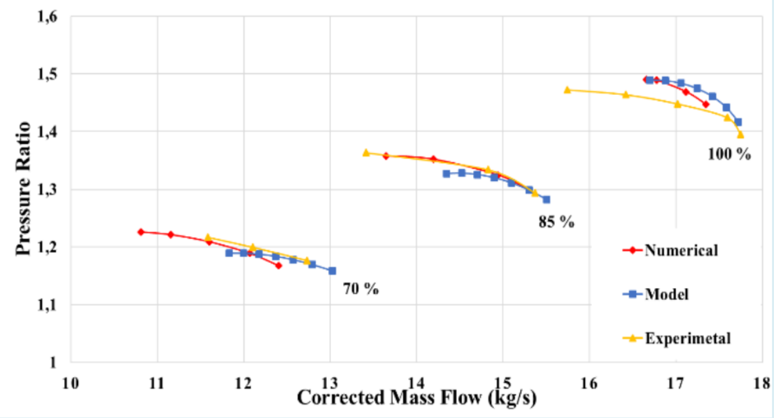


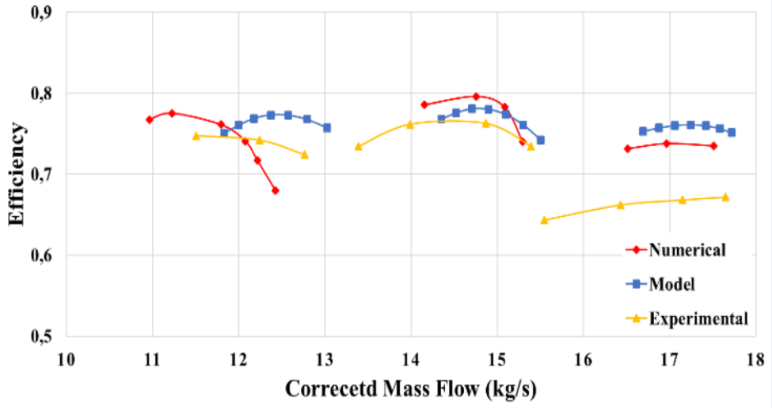
Validation Cases

Distorted Compressor Validation

- Compressor performance under inlet distortion
- **DFVLR transonic single-stage compressor[17]**
- Distorted inlet section
  - 120° extent
  - 7.66% pressure drop
- Distorted map at 70/85/100% corrected speeds

Mean Relative Errors (%)			
Model (aPQ=1,02)	**PR**	**Efficiency**	**PRS**
Vs. Numerical[17]	0,67	3,1	2,34
Vs. Experimental[17]	1,26	6,53	-





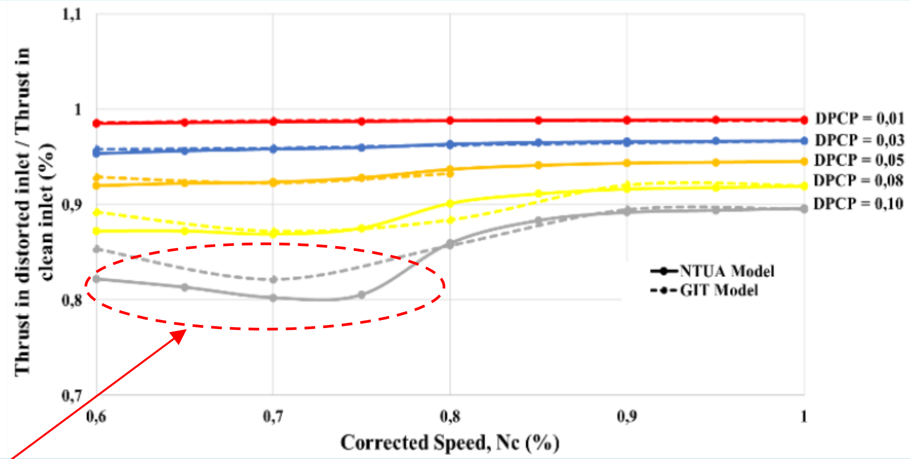
- ✓ **Sufficient agreement** in predicted PR at all examined speeds compared to both numerical and experimental data
- ✓ **Sufficient agreement** in predicted efficiency compared to numerical results and at lower speeds regarding the experimental data

[17]M. Lecht, "Improvement of the Parallel Compressor Model by Consideration of Unsteady Blade Aerodynamics", AGARD-CP-400, Conference Proceeding No. 400, Engine Response to Distorted Inflow Condition

Validation Cases

Propulsor Validation

- Impact of inlet distortion on gross thrust production
- **High pressure PW1128 compressor (GIT Model)** [16]
- Distorted inlet section
  - 180° extent
  - Various examined distortion intensity levels (DPCP)



✓ **Sufficient agreement** for each examined distortion case at high speeds

✓ Deviations of 3% occurred at low speeds (<80%) for the highest examined distortion case even though the mean error lied to 1.5% for DPCP=0.10

DPCP parameter	0.01	0.03	0.05	0.08	0.10
Error in thrust (%)	0.05	0.14	0.53	1.01	1.35

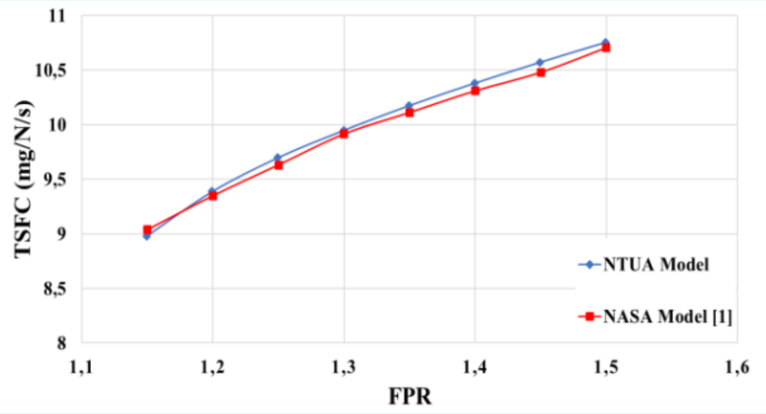
[16] Pokhrel, M., Gladin, J., Garcia, E., Mavris, N., "A Methodology for Quantifying Distortion Impacts using a Modified Parallel Compressor Theory", Proceedings of ASME Turbo Expo 2018, Oslo, Norway, GT 2018-77089, 2018.

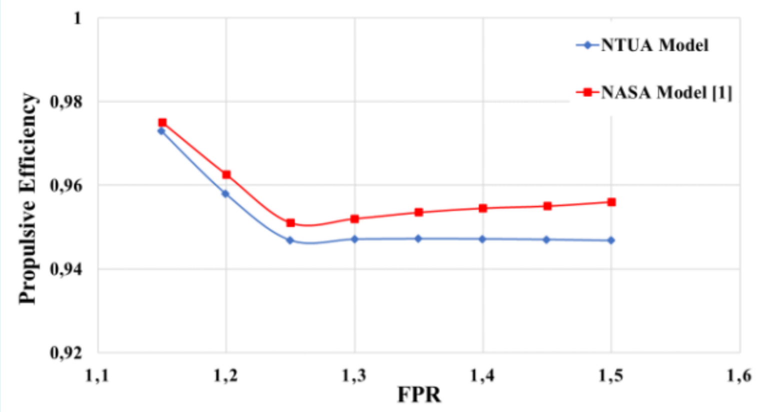
Validation Cases

TeDP Model Validation

- BLI TeDP system performance
- **N3-X aircraft propulsion system (NASA Model) [1]**
- Design point parametric analysis of FPR
    - Alt = 30000 ft, MN = 0.84
    - Total Thrust = 118.99 kN
- Averaged common inlet conditions are considered for propulsors array
    - MN = 0.81
    - δ_{BL} = 0.4572 m

✓ **Sufficient agreement** in predicted TSFC and propulsive efficiency (both provided mean deviations about 0.6%)





[1] Felder, J. L., Kim, H. D. and Brown, G. V., "An Examination of the Effect of Boundary Layer Ingestion on Turboelectric Distributed Propulsion", 49th AIAA Aerospace Science meeting, 2011.

Test Cases

Methodology

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Test Cases

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Summary & Conclusions

Test Cases

A **Design Point Calculation** is carried out in **two steps** :

1st Step

- Averaged common inlet conditions applied for all propulsors
- Aim of this initial stage
  - Preliminary design of propulsors **(propulsor inlet duct height, fan tip diameter, fan map scaling factors, nozzle exit area)**
  - Preliminary design of turboshaft engine **(compressor/turbine map scaling factors, nozzle exit area)**

2nd Step

- Adjustment of local inlet conditions to each propulsor unit separately
- MN and δ_{BL} distributions are required[1]
- Provided results of 2nd step → Estimation of BLI TeDP system performance

[1]Felder, J. L., Kim, H. D. and Brown, G. V., "An Examination of the Effect of Boundary Layer Ingestion on Turboelectric Distributed Propulsion", 49th AIAA Aerospace Science meeting, 2011.

Test Cases

Design Point and Propulsion System Performance Parameters at Aerodynamic Design Point of N3-X aircraft

- 2 turboshaft engines and 14 propulsors in total
- MN distribution : 0.8 … 0.82 and δ_{BL} distribution : 0.447 … 0.46 m

Propulsion System Parameters

Alt = 30000 ft
Flight MN = 0.84
Total Thrust = 118.99 kN
TSFC = 9.95 mg/N/s
Thrust Split Ratio = 0.927
Total Power = 28.2 MW
eBPR = 28.18

Propulsor Parameters

FPR = 1.3
Fan Efficiency = 0.954
Fan Tip Diameter = 1.097 m
Inlet Duct Height = 0.73 m
Inlet Duct Width = 1.219 m (1)
Inlet Losses = 0.2% (1)
Nozzle Exit Area = 0.6585 m^2

Turboshaft Parameters

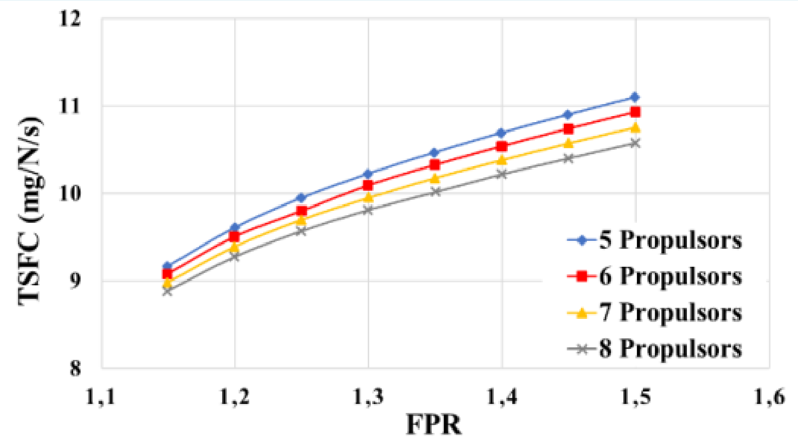
Mass Flow Rate = 23.41 kg/s
TIT = 1811.1 K
LP spool speed = 7000 rpm
HP spool speed = 10000 rpm
OPR = 74.8
Nozzle PR = 1.63
Nozzle Exit Area = 0.3301 m^2

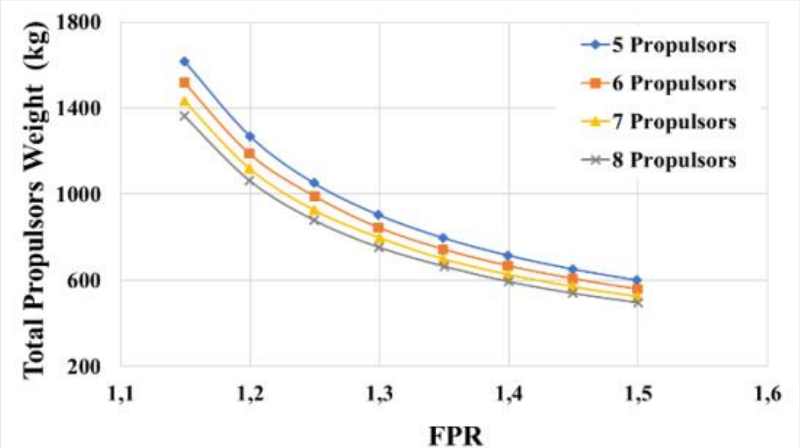
[1]Felder, J. L., Kim, H. D. and Brown, G. V., "An Examination of the Effect of Boundary Layer Ingestion on Turboelectric Distributed Propulsion", 49th AIAA Aerospace Science meeting, 2011.

Test Cases

Configurations with Different Number of Propulsors

- 5 to 8 propulsors are examined for the half array configuration
- Constant propulsor inlet width at 1.219 m constrained by 20 m aircraft span
- Increasing FPR leads to higher TSFC, but lower weight levels
- Increasing the number of propulsors leads to lower TSFC and weight levels





Test Cases

BLI gains for different number of propulsors

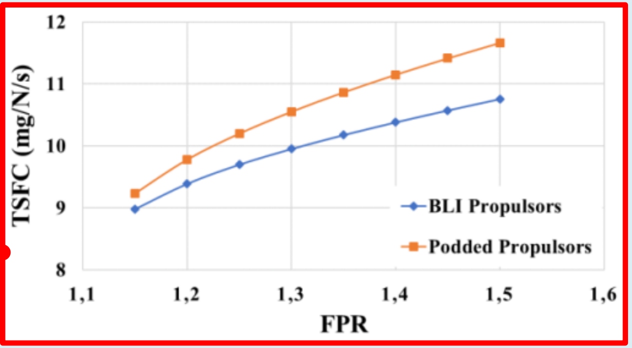
- Two TeDP configurations are examined to assess and quantify the BLI benefits
  - BLI TeDP system → BLI propulsors
  - Non BLI TeDP system → Podded propulsors exposed to freestream air
- The two configurations are compared at the same thrust requirement

✓ **All the examined number of propulsors revealed a TSFC reduction and n_p increase at all FPRs**

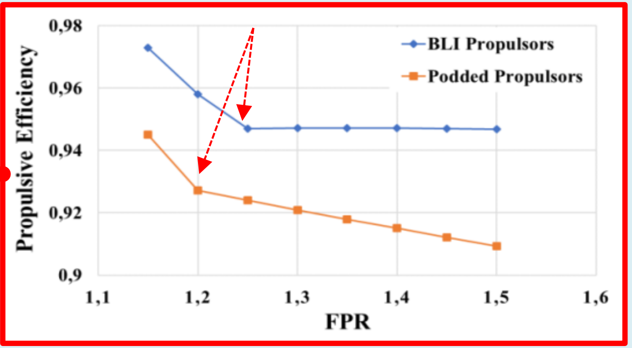
✓ **Weight also improves with more BLI propulsors but this trend is not observed at low FPRs where BLI resulted in greater weights**

✓ **Increasing the number of propulsors → BLI gains get higher in terms of TSFC and n_p improvement**

Maximum ΔTSFC = -9.32 % @ 16 propulsors in total
Maximum Δn_p = +4.72 % @ 16 propulsors in total



14 propulsors in total



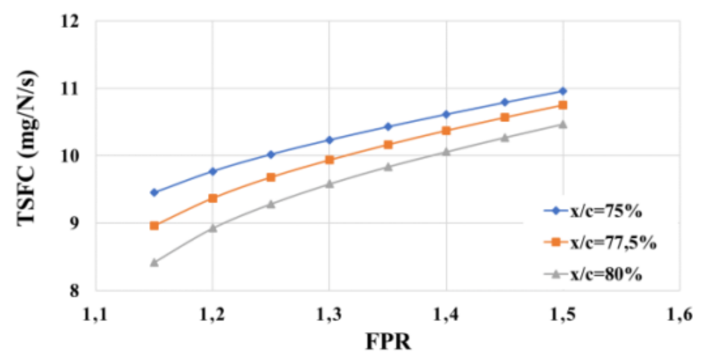
Test Cases

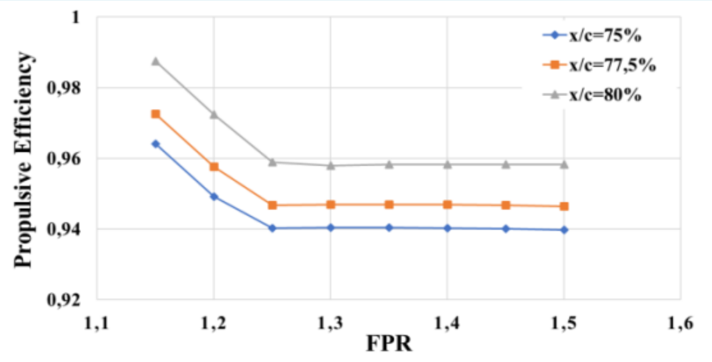
Different Propulsors Array Location

- 3 different propulsors array locations of 14 propulsors are examined alongside the aircraft centerline
- Each location is described as fraction of centerline x/c
  - x/c = 75% (frontwards) → MN = 0.82 / δ_{BL} = 0.432 m
  - x/c = 77.5% (reference location) → MN = 0.81 / δ_{BL} = 0.457 m
  - x/c = 80% (rearwards) → MN = 0.8 / δ_{BL} = 0.508 m

  Averaged inlet characteristics of each position
- MN and δ_{BL} distributions are applied at each case[1]

✓ **Moving the propulsors array rearwards improves TSFC and n_p, but increases the inlet distortion level to the propulsors**





[1]Felder, J. L., Kim, H. D. and Brown, G. V., "An Examination of the Effect of Boundary Layer Ingestion on Turboelectric Distributed Propulsion", 49th AIAA Aerospace Science meeting, 2011.

Summary & Conclusions

Summary & Conclusions

- A modelling approach of BLI TeDP systems considering the influence of inlet distortion was presented. The aim of this study was to estimate and quantify the BLI benefits on the performance of TeDP propulsion systems. The N3-X propulsion system was modelled in PROOSIS, developing a model of BLI TeDP system.

- The accounting of inlet distortion which a BLI propulsor faces allowed to assess the impact of the MN and δBL distribution alongside the propulsors array instead of considering a common averaged inlet for all propulsors.

- Each developed model in PROOSIS was validated by comparing it to numerical and/or experimental data.

- Design point calculations were carried out in two phases, by firstly applying a common averaged inlet condition to all propulsors for establishing their key dimensions. In the second phase, the actual performance of the propulsion system was estimated by adjusting to each propulsor its own local inlet condition

- The impact of the number of propulsors and their array location on performance levels were studied, aiming to assess the BLI gains for each examined configuration

  - **Increasing the number of propulsors results in greater improvements in terms of TSFC, np and weight reduction**
  - **BLI gains increase at higher FPRs, while BLI implementation may increase the weight of propulsion system at low FPRs**
  - **A maximum reduction of TSFC about 10% and increase of np about 5% can be achieved for 16 propulsor units**
  - **Moving the propulsors array location rearwards increases the BLI benefits but also the inlet distortion to the propulsors**

TURBOELECTRIC DISTRIBUTED PROPULSION MODELLING ACCOUNTING FOR FAN BOUNDARY LAYER INGESTION AND INLET DISTORTION

Thank you for your attention !