Mechanical Components Design for a Hybrid Assisted Regenerative Turbofan Engine (HARTFE) Configuration for Future Aircraft propulsion

Ussama Hamid, Hamza Tariq, Ali Sarosh, Farhan Tariq and Rizwan Yousaf

June 5, 2023

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Ussama Hamid [1]
Dept. of Mechanical & Aerospace Engineering. Air University
Air University,
Islamabad, Pakistan

Dr. Ali Sarosh [1]
Dept. of Mechanical & Aerospace Engineering. Air University
Air University,
Islamabad, Pakistan

Hamza Tariq [1]
Dept. of Mechanical & Aerospace Engineering. Air University
Air University,
Islamabad, Pakistan

Farhan Tariq [1]
Dept. of Mechanical & Aerospace Engineering. Air University
Air University,
Islamabad, Pakistan

Rizwan Yousuf [2]
CAE. National University of Science & Technology
National University of Science & Technology, NUST
Islamabad, Pakistan

Abstract— **Increasing energy demand, varying fuel prices, and worldwide carbon emissions reduction drives have led researchers to develop hybrid engines for the aviation industry. The concept of electrical assisted and electrical driven hybrid engines is gaining pace with advancements in electrical motors and Li-ion batteries. This research focuses on developing electro-mechanical components for a hybrid-assisted regenerative turbofan engine (HARTFE) configuration. This modification aims to reduce the operating cost of the commercial aircraft while sustaining greener airport operations for future air travel by the year 2035. To attain this objective a baseline regenerative turbofan engine has been proposed so that the gas turbine engine can be used in the hybrid mode for electrical operation instead of fossil fuel consumption. Several design changes are introduced, downstream of the turbines and upstream of the compressor, to provide complete electric taxi and electric-assisted (Hybrid) takeoff operation. The components include the electro-mechanical clutch (downstream of the turbine) and bypass shielding mechanism (upstream of the compressor). Closed cycle analysis is also performed to evaluate the engine parameters in the hybrid assisted versus no hybrid behaviour. Overall engine design analysis shows that during takeoff 375kg of fuel can be saved along with the removal of 280kg auxiliary power all at 2.43% of a weight penalty.**

Keywords

Hybrid Assist, Turbofan engine, switch reluctant motor, parametric cycle analysis, turbine-compressor matching, degree of hybridization, magnetic clutching

I. INTRODUCTION

With technological advancement, the cost of air travel is decreasing worldwide. Due to this, more population is switching to air travel for low-cost and fast travel. Modern survey of travel shows that air travel is predicted to continue to rise steadily at a rate of approximately 3.6% per year [1]. This steady growth is leading to an increase in carbon emissions hence contributing to air pollution, increasing noise pollution at airports, and depleting natural oil reserves at a rapid pace. Given the foregone, international bodies including European Union, International Air Transport Association (IATA), International Civil Aviation Organization (ICAO) and NASA have set ambitious goals to reduce carbon emissions by developing and encouraging greener aircraft and airports [2]. Therefore, the concept of hybrid engines for the aviation industry has been highlighted [3]. The concept of electrical assisted and electrical driven hybrid engines is gaining pace with advancements in electrical motors and high capacity batteries [4].

The engine is triple spool with unmixed exhaust and consists of a Low-Pressure Compressor (LPC) mechanism connected to a Low-Pressure Turbine (LPT). Similarly, the Intermediate Pressure Compressor and the High-Pressure Compressor are driven by the Intermediate-and High- pressure turbines (IPT), (HPT) respectively [5].

Rizwan and Sarosh et al have proposed a HARTFE configuration that is based on providing an initial step towards the conceptual design of the hybrid configuration [5].

Based on the aforementioned work, in this research, a baseline regenerative triple spool turbofan engine has been used for evolving the electromechanical components for HARTFE configuration. This provides the design of electro-mechanical components necessary to provide full electric taxi and hybrid-assisted electrical take-off operation with the overall objective of cutting down the operating cost while supporting greener operations.

II. CONCEPT

The research is based on the concept that two different degrees of hybridization can be achieved by integrating the electromechanical components into the flow field of a triple spool turbo-fan engine. The power generation is essentially supported through an electro-mechanical mechanism placed downstream of the turbine while the hybrid-mode operation will require a compressor-shielding mechanism during electrical operation mode.

The integration of mechanical diaphragm, an iris shaped module, for the compressor shielding to redirect entire air to bypass during taxi operations and electro-mechanical clutch for electro-mechanical shaft power transmission from an electric motor to Low-Pressure Turbine hence allowing independent integration of fan with motor for less power consumption

III. METHODOLOGY

The conceptual design of a HARTFE configuration is produced and analyzed for performance improvement [5]. Therefore, the component matching is to be performed for the thermodynamic parameter to support the hybrid-assisted operation. Research is carried out to analyze the design of HARTFE engine produced at CAE NUST, selection of suitable hybrid operating mode, performing large system analysis using GasTurb13®, selection of hybrid assist configuration, design of electro-mechanical power transmission component, design of mechanical component for compressor shielding and structural integrity of components. Figure 1 shows the research process steps in a flowchart diagram.

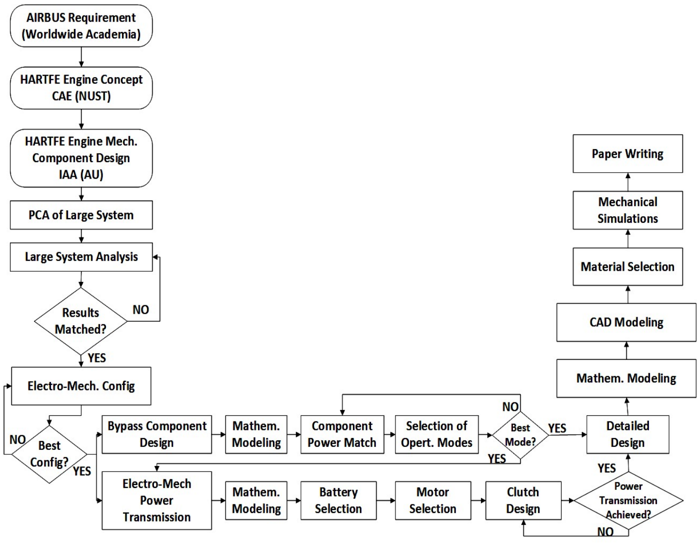

Figure 1: Research process flowchart

Figure 2 shows that after first stage fan compressor shielding mechanism known as mechanical diaphragm is to be installed and after low pressure turbine downstream mechanical node & clutch mechanism and electromechanical transmission mechanism is to be installed.

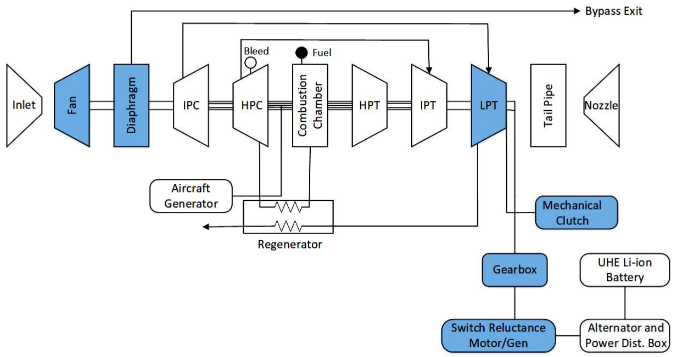

Figure 2: Modified HARTFE engine from the baseline Trent XWB engine

Real Parametric Cyclic Analysis (PCA) of the modified engine has been carried out in GasTurb13® which is a commercial gas turbine performance simulation software [6]. Station wise data for normal takeoff and power requirement for normal taxi has been obtained from the CAE NUST design team. Through large system analysis, three flight operations which include electric taxi, normal take-off, and hybrid assisted take-off have been simulated, a parametric study of performance and flow parameters have been carried out and thermodynamic cycle adjustment has been carried out to obtain desirable results for component designing, electromechanical transmission, and hybrid assist configuration. Low-pressure spool compressor and turbine performance assessment have been carried for normal take-off and hybrid assisted take-off.

Mechanical efficiency for turbine stages has been kept 98%. The first step in PCA is to calculate corrected mass flowrate which is widely used in the analysis and calculations. It is obtained from mass flowrate, temperature and pressure in the expression which is defined as

$$Wcorr = W \,.\, \frac{\sqrt{\dfrac{R\,.\,T}{Rstd\,.\,Tstd}}}{\dfrac{P}{Pstd}}$$

Then we go for primary spool speed. The relative spool speed is defined as N, relative = N / N,ds with N,ds = 1.0 at the cycle design point.

The actual spool speed is N = N, relative * N, nominal

The relative corrected spool speed is defined as

$$Ncorr,rel = \frac{N/\sqrt{\dfrac{R\,.\,T}{Rstd\,.\,Tstd}}}{\left(N/\sqrt{\dfrac{R\,.\,T}{Rstd\,.\,Tstd}}\right)_{ds}}$$

For the cycle design point the relative corrected speed is per definition 1.0. Most vital step in determining the performance of an engine is to calculate the thermal, propulsive and overall efficiencies. The efficiency of an aircraft engine is inseparably linked with the flight velocity. Specific fuel consumption (SFC) is a mostly used performance parameter and used to compare quality of engines and defined as:

$$SFC = \frac{Vo}{\eta core\,.\eta trans\,.\,\eta p\,.\,FHV}$$

The regression curve for the batteries was analyzed and based on those results it was found out that fully electric taxis will be supported by these batteries by the year 2035.

Clutch was installed downstream of the turbine for power transmission to the First stage compressor.

To make the engine Hybrid for take-off operation the values at iteration number 22 (discussed is the “analysis and discussion section”) were considered and were taken as a design point. The power at this point was 9MW less than the required power, which was covered by the electrical system, hence obtaining a hybrid system.

On the downstream of the first stage compressor, a diaphragm was integrated to divert the air to the bypass instead of the core as per operation i.e. taxi, take-off, etc. During the electric taxi, when the clutch is engaged, the diaphragm will be deployed to divert the air to the bypass to maximize the thrust obtained during this operation.

IV. RESULTS

After performing several iterations, we finally came up with the required point i.e. iteration number 22. At the 22nd iteration, it is concluded that we can make-up the rpm and thrust loss by electrical power. Thus, iteration 22nd becomes our design point for hybrid assist take-off. Flow parameters at iteration 22nd determined are given below.

Critical Computed Flow Parameters (Hybrid Assisted Take-off)						
Parameters	**Station 2**	**Station 21**	**Station 13**	**Station 48**	**Station 5**	**Station 8**
Mass Flow [kg/s]	1281.88	122.256	1159.63	118.659	118.659	118.659
Stagn. Temp. [K]	288.15	321.571	321.267	1027.1	712.1	712.1
Stagn. Pressure [kPa]	100.312	142.251	142.251	565.884	106.978	106.978
Velocity [m/s]	148.16	161.926	165.99	302.84	217	14.463
Cp @Ts [J/kg-K)]	1004.25	1005.55	1005.48	1171.43	1099.71	1102.69
Enthalpy @Ts [J/kg]	21005.9	10500.2	9525.93	752039	413901	426426
Fuel-Air Ratio	0	0	0	0.018453	0.018453	0.018453

Table 1: Critical Computed Flow Parameters for Hybrid Assisted Take-off

Critical Computed Performance Parameters		
Parameters	**Units**	**Values**
Net Thrust	[kN]	291
TSFC	[g/(kN*s)]	7.37
Core Thermal Efficiency	%	46%
Primary Spool Speed N1	[RPM]	11520

Table 2: Critical Computed Performance Parameters for Hybrid Assisted Take-off

The map is limited to the left by the surge line. This is the limitation of the airflow at the compressor inlet. The choke line is the rapidly descending line on the right of the compressor map. Surge margin provides a measure of how close an operating point is to surge. The top line is the maximum performance of the envelope. Compressor and turbine maps are plotted with corrected mass flowrate on the x-axis and stagnation pressure ratio on the y-axis in which efficiency islands vary. In map figures, the white circle (point B) marks the normal take-off setting while the yellow square (point A) marks the hybrid assisted take-off setting. Figure 3 shows compressor map and comparing normal take-off and hybrid assisted take-off corrected mass flowrate decrease from 1415 [kg/s] to 1260 [kg/s], pressure ratio decreases from 1.5 to 1.42 and efficiency increase from 0.88 to 0.91.

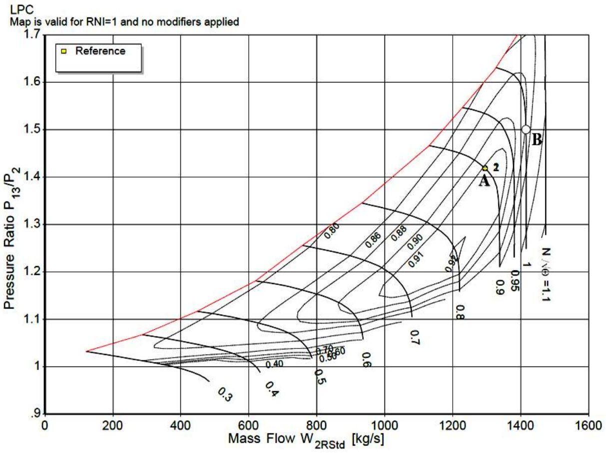

Figure 3: Hybrid assisted take-off compressor map

Figure 4 shows the turbine map and comparing normal take-off and hybrid assisted take-off, turbine maps efficiency is shifting the efficiency island but it lies in the same efficiency island which is 0.90 but low spool speed decrease from 12800 [rpm] to 11520 [rpm] with reduction in fuel mass flowrate and temperature and pressure.

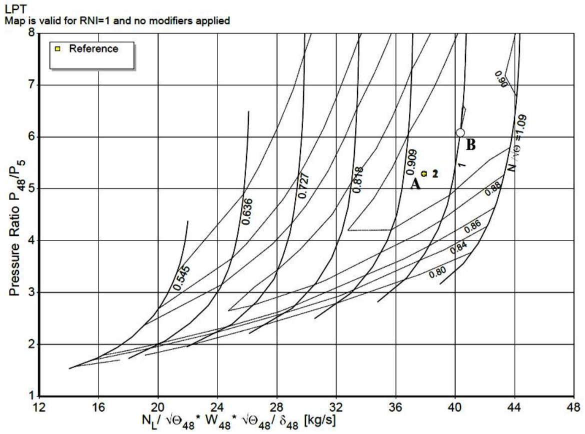

Figure 4: Hybrid assisted take-off turbine map

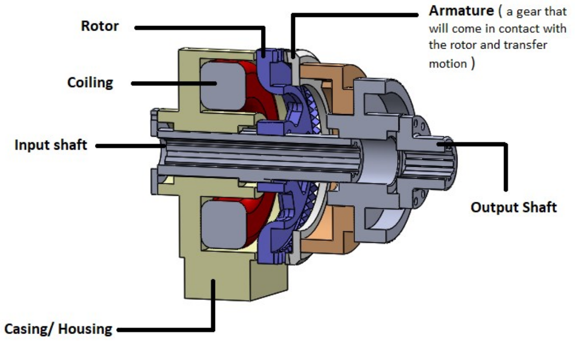

Figure 5: Stationary Field Tooth Clutch

Figure 5 shows the CAD model of the electromagnetic clutch. It will engage and disengage the LPT from HPT and IPT as per requirement. It will be working on “fail-safe operation” and in case of failure, it will connect LPT back to IPT and HPT hence the factor of safety is maximized.

Figure 6 shows the conceptual design which best describes our project. There is a battery as well as a fuel supply. It can be seen that both of these systems i.e. battery integrated with the conventional engine will make the engine hybrid.

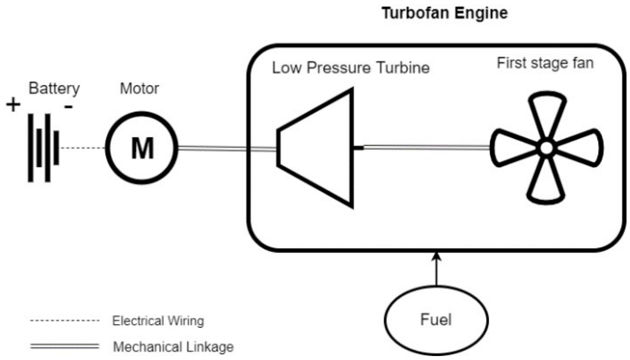

Figure 6: Parallel electromechanical transmission configuration

Figure 7 shows the whole rear assembly. As discussed in the "Analysis and discussion" section the engine has to be tail mounted for this configuration. Hence this figure shows the assembly for the tail mounted engine.

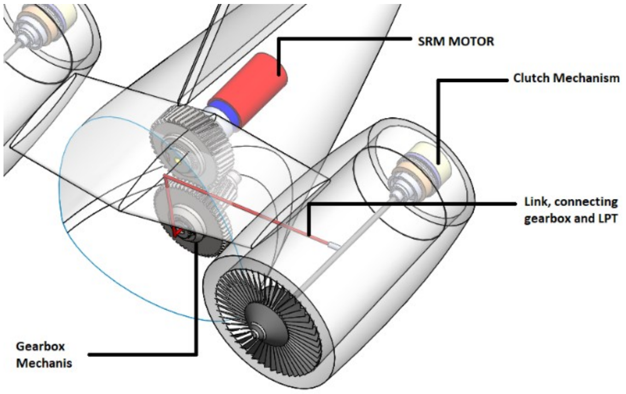

Figure 7: Tail engine configuration

Table 3 shows the results obtained for the Electric Taxi mode. CFD results are compared with the analytical calculation of the stage no.21 (which is after turbofan) and stage no.22(which is the core inlet) because diaphragm is present between those 2 stages of the engine.

Comparison of Analytical and CFD Results of Electric Taxi Mode				
Parameters	Station no.21	Diaphragm Surface	Station no.22	Variation
Absolute Pressure	122.380 kPa	101.414 kPa	122.380 kPa	17 %
Absolute Temperature	306.246 K	300 K	306.273 K	1.97 %

Table 3: Comparison of analytical and CFD results of electric taxi

There is a difference of 17% in the result of our Absolute pressure and 1.97% of difference in our absolute temperature. These results are quite acceptable because we are able to achieve 80% of the value that we obtained it our analytical calculation.

Table 4 shows the results obtained from hybrid Assisted Take-off mode. CFD results are compared with the analytical result of iteration no.22 (performed using the Gasturb ® software) CFD results are compared with the values of the stage no.13 (which is after turbofan in bypass) and stage no.16 (which is in the bypass) because diaphragm is present between those 2 stages of the engine during Hybrid assisted takeoff mode.

Comparison of Analytical and CFD Results of Hybrid Assisted Take-off Mode				
Parameters	Station no.13	Diaphragm Surface	Station no.16	Variation
Absolute Pressure	142.251 kPa	138.55 kPa	138.978 kPa	2.69 %
Absolute Temperature	321.267 K	339.96 K	321.267 K	5.5%

Table 4: Comparison of analytical and CFD results of hybrid assist take-off

There is a difference of 2.69% in the result of our Absolute pressure and 5.5% of difference in our absolute temperature results. These results are quite accurate and verified the analytical result of the iteration no.22 which was performed on Gasturb ® software to achieve the Hybrid Assisted Takeoff mode.

The followning table discusses the power deliverance, fuel consumption (Percentage savings) and turbine efficiency in concrete numbers.

Parameters	**Conventional Mode**	**Hybrid Mode**	**Percentage Saving**
Power Distribution Take-off	From Engine= 132 MW From Batteries= 0 MW	From Engine= 123 MW From Batteries= 9 MW	---
Fuel Consumption Taxi for 10 minutes	160.7 kg	0 kg	100%
Fuel Consumption Take-off for 30	95.4 kg	64.5 kg	32%
Low Pressure Turbine Efficiency	88%	87.30%	---

Table 5: Power Distribution & Fuel Saving

V. ANALYSIS AND DISCUSSION

The goal of large system simulations is that the aircraft at taxi shall be powered completely through electrical motors. Whilst at take-off and cruise, electrical power shall contribute to total engine thrust. Through large system analysis, it is proved through calculations that we have enough electric power to perform an electric taxi. Engine power is completely shut off during taxi while power will be provided by electric power source through electromechanical transmission mechanism to low-pressure turbine.

Various iterations were performed which include two approaches: first is by minimizing air ($\dot{m}a$) mass flowrate and adjusting Brayton cycle and the second is by minimizing fuel ($\dot{m}f$) mass flowrate and adjusting Brayton cycle as a result 2 breakpoints are obtained. Breakpoint obtained through minimizing $\dot{m}a$ is called Breakpoint 1 while minimizing $\dot{m}f$ is called Breakpoint 2.

In the case of air mass flowrate minimization iterations, thrust specific fuel consumption (TSFC) increases net thrust decreases, fuel mass flow rate and core thermal efficiency slightly decrease while the cycle maximum and stations pressure and temperature remain constant. Also, the spool speed remains the same. While in the case of fuel mass flowrate minimization iterations, TSFC decreases, net thrust decreases, air mass flow rate decreases with a slight reduction in core thermal efficiency. In this case cycle maximum and stations, temperature and pressure does not remain the same. They decrease. Also, the spool speed is reduced.

Through analytical analysis of these two points, we have obtained our desired design point where hybrid assisted takeoff will be possible and electric contribution will full fill the power loss, experienced due to a decrease in the mass flow rate of fuel.

Through large system analysis, it is proven that the simulation engine model results are close to the engine manufacturer data in terms of TSFC, temperatures, pressures, mass flowrate, thermal efficiencies, and net thrust during takeoff and taxi operations. Large system analysis results are more accurate due to including component modeling during analysis. The take-off and taxi TSFC were in general predicted within 2% error when compared to engine manufacturer performance data. The take-off and taxi net thrust were in general predicted with less than 10% error.

Performance assessment of low spool compressor and turbine is carried out by compressor mapping and turbine mapping by embedding simulation data into sample maps on GasTurb13®. The engine has core thermodynamic efficiency variation from normal take-off to hybrid assisted take-off with value from 48% to 46%. In hybrid assisted take-off core thermal efficiency is reduced with reduction in amount of air mass flowrate and fuel mass flowrate. Thus, hybrid assisted take-off which is off design point shifts from normal take-off design point to the left and downward side on the map towards surge line.

The clutch is supposed to connect the low-pressure turbine with the first stage compressor (fail-safe operation) i.e. fan, during the taxi operation which will be able to give us a degree of hybridization of 1, which means that taxi is going to be fully electric. This concept has been shown in the figure below.

Figure 8 shows the conceptual model of the degree of hybridization in which there are 2 extrema in this figure. One is the (0,0) which means that the degree of hybridization is equal to 0 and all the power is being delivered by the fuel. And the coordinate (1,1) shows that all the power is being supplied by the electrical system. Our project lies in between these two extrema, indicated by a red pointer which shows DOF of 0.07, as it is a commercial aircraft and we cannot afford a fully electric take-off.

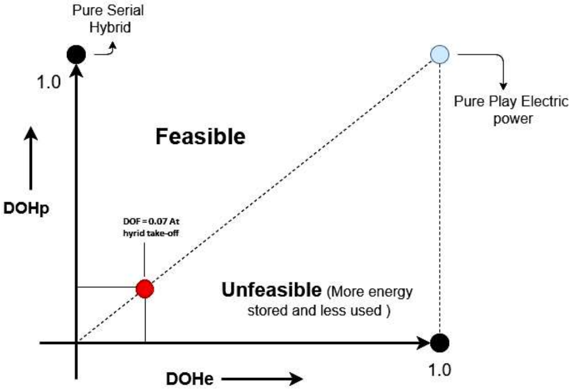

Figure 8: Degree of hybridization conceptual model

This electrical system is incorporated in the engine to supply the remaining (9MW) amount of power. Because of the decrease in the fuel mass flowrate, in the iterations performed in large system analysis, we have a shortfall of rpms of the turbine. To counter this rpm loss, we had to integrate a gearbox in order to achieve the desired rotational speed of the LPT for hybrid takeoff. With the engine on wing we faced a designed constraint for the installation of gear box and motor so we opted for tail mounted engine Therefore, a conceptual design was made for the tail mounted engine which gave us the liberty to connect the motor and LPT easily.

Three different design configurations of mechanical diaphragm were designed, out of which “Strut supported diaphragm in the bypass duct” was considered the best option by our team. Figure 9 shows the 3d model of selected diaphragm mechanism.

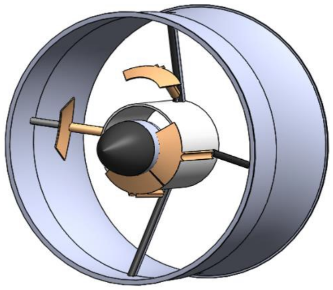

Figure 9: Strut supported diaphragm in bypass duct

This design is selected as it doesn’t produce any stagnation points when it is in retracted mode and easily by-pass the coming air flow.

After performing the analytical calculations and designing the mechanical diaphragm we performed the CFD analysis using Ansys® Software to verify those analytical calculations. CFD has been performed in two steps:

1. Mesh Refinement
2. CFD Analysis

We have performed 7 Iterations for the mesh refinement Figure 10 shows that we have performed iterations using seven different mesh sizes and compared the value of absolute pressure.

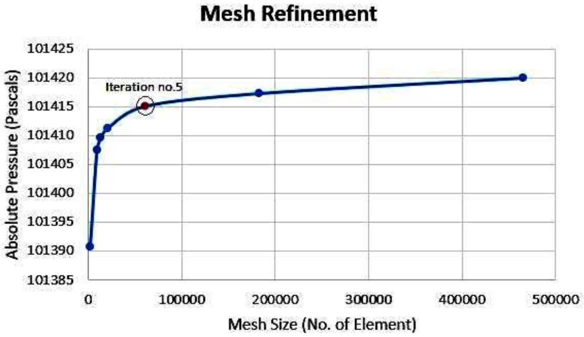

Figure 10: Solution behavior according to mesh size

From this plot we can easily judge that after our 5th Iteration an asymptotic behavior of the solution starts to emerge, and the changes in the solution between meshes become smaller. Along with that value of the absolute pressure at our desired mesh size in 5th iteration is 101415 Pa which is exactly the 80 % of our value, 128000 Pa, which was calculated analytically. Hence not only our Analytical calculation has been verified but we have also been able to select our desired mesh size on which we can perform our 2nd step which is CFD Analysis.

CFD analysis of 2 modes are performed which are as following:

1. CFD analysis of Diaphragm at Electric Taxi mode.
2. CFD analysis of Diaphragm at Hybrid Assisted Take-off mode

During taxi mode Diaphragm will be at 65° angle to the central axis of LPT shaft, blocking the core. In Take-off Mode Diaphragm will be at 50° angle to the central axis of LPT shaft, allowing electric assisted takeoff.

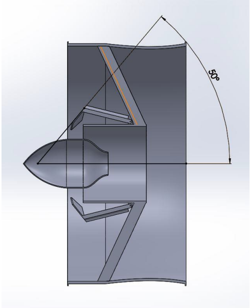

Figure 11a: Diaphragm in hybrid assisted take-off

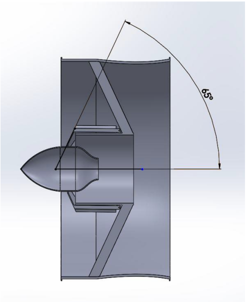

Figure 11b: Diaphragm in electric taxi

We performed CFD analysis for achieving convergence. The steps involved are:

1. Steady state, Inviscid flow and without Energy Equation.
2. Steady state, Inviscid flow and with Energy Equation.
3. Steady state, Laminar flow and with Energy Equation.
4. Steady state, Turbulent flow (S-A Equation) and with Energy Equation
5. Steady state, Turbulent flow (k-ε Equation) and with Energy Equation.

For Electric Taxi Mode we used velocity inlet and pressure outlet boundary condition and the velocity magnitude is set equal to 8 m/s and pressure is set equal to 0 Pa. For Hybrid Assisted Takeoff Mode we used the same velocity inlet and pressure outlet boundary condition and we see that the inlet velocity of air to be equal to 166 m/s and outlet pressure to be equal to 119406 Pa. SIMPLE, Semi Implicit Pressure Linked Equation, the scheme is used as a solution method and Hex-Dominant mesh type is used

VI. Conclusion

Hence it is concluded that the designed electromechanical components can be produced and can be integrated into the engine to support the electrical operation as well as the hybrid operation. The electromechanical clutch is to be placed downstream of the turbines and connected to the LPC via LPT spool, where a shielding mechanism will be providing the bypass operation. The aerodynamic analysis shows that there are no stagnation points in the Strut supported diaphragm hence it is the most suitable design.

For a complete electrical taxi, the diaphragm has to be deployed to bypass the air meanwhile the electromagnetic clutch disengages the LPT from IPT and HPT so that LPT will only be connected to the low-pressure compressor or Fan.

Gesture analysis shows that we can extract the desired amount of power from the turbines by decreasing the mass flow rate of fuel so that the difference in the actual power needed for takeoff and the modified power can be achieved by the electrical system.

During takeoff, the diaphragm will be deployed partially, and the clutches will disengage, hence providing an electric-assisted takeoff.

Moreover, this configuration is for the “tail-mounted engines” as the links have to be designed and which will not be supported by the engines on wings.

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