DESIGN OF A COMPETITIVE AXIAL TURBINE FOR A DOWNSIZED TURBOCHARGED IC ENGINE

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INTRODUCTION

The continue research for engine efficiency improvements is one of the major challenges of the last decades, leading to the design of highly downsized boosted engines. Among other boosting strategies, turbocharging allows to recover part of the exhaust gas energy, improving the overall efficiency of the power unit. However, turbochargers lead to less responsive power units because of the widely known turbo-lag effect due to the inertia of the rotating parts in the system. With engine manufacturers testing different concepts to reduce this effect, for both commercial and motorsport applications, this work is about the development of a low inertia turbocharger axial turbine, evaluating pro and cons of several design solution. The idea is to initially evaluate the performance (mainly efficiency) difference between prismatic and twisted blades turbine for different size ranges. In fact, as one of the issue of axial turbines compared to radial ones is the production cost, the use of low aspect ratios blades, in such a way to minimize the difference between the use of 3D optimized turbines and prismatic turbines, should allow for more cost-effective extruded type blade solutions to be implemented.

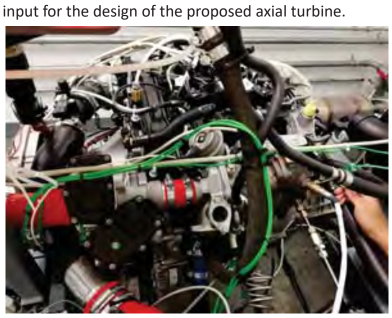
REVERSE ENGINEERING

Initially the OEM turbocharger was disassembled and **3D scanned**. This process allowed for accurate mass distribution calculations (particularly the rotational moment of inertia) without the need of designing accurate test benches and conduct other experiments. Further, the 3D scans will be used to complete the mechanical design of the turbine housing as they precisely define the interfaces with the original exhaust manifold, wastegate actuator and the other main components. The scanned meshes were repaired, remeshed and **reconstructed with ANSA and SolidWorks**.

From left to right - 3D optical measurement with blue light fringe pattern projector and stereoscopic cameras - turbine seen from the scanner cameras - dome of images acquired by the sensors - Example of mesh repair on the turbine rotor - Comparison between the scanned turbine mesh and the repaired CAD

ENGINE MODELLING

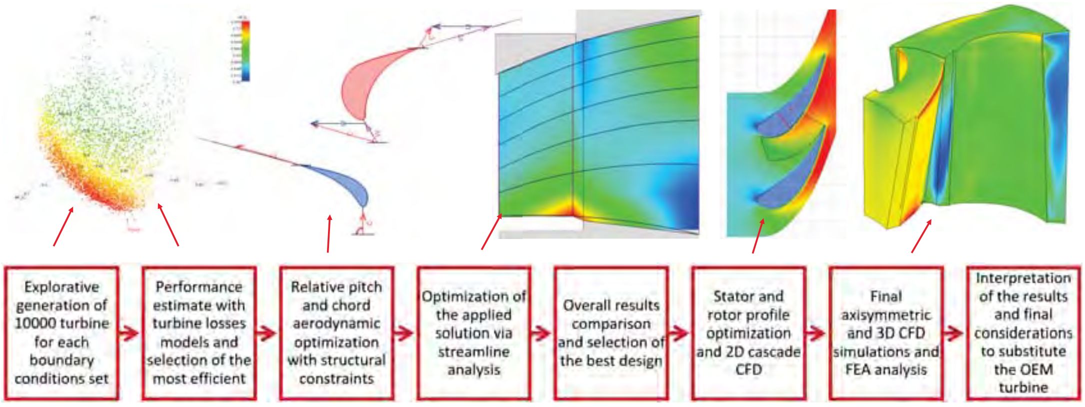
The fluid dynamics boundary conditions were obtained, for different engine speeds at full load, through **simulations with Ricardo Wave on a 1D model,** which was calibrated at the University automotive labs with engine **dyno tests**. The resulting data was processed and used as input for the design of the proposed axial turbine.



Engine on the dyno

TURBINE DESIGN METHODOLOGY

The preliminary design of the turbines was performed with **AxSTREAM** following the process described below. Performant turbines can be designed thanks to increasingly accurate DoE methods. Over 10000 turbines were generated for each type (6 types), then optimizing the selected ones to reduce the losses.



TURBINE PRELIMINARY DESIGN AND PERFORMANCE COMPARISON

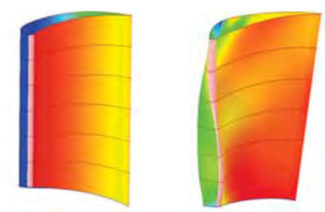
Given the strong dependence of the total to static efficiency with the blade speed ratio of the rotor (U/c_0), **multiple size ranges were preliminary designed** in order to choose the most performant turbine solution considering all the relevant variables.

The results of the preliminary design are summarized in the table and show a clear **advantage of the smaller range turbines** despite the lower efficiency in respect of bigger ones. In fact, the main KPI was the **spool up factor (dω/dP)**, a parameter which indicates how responsive is the turbine to changes in the energy rise of the exhaust gas.

Then, the **estimated costs** for the manufacturing process of the prismatic, twisted and OEM turbines were calculated **via CAM programs** by an external company and were used to quantitatively measure the benefits of the final choice.

Rotor data	Range 1		Range 2		Range 3		Baseline
Properties	Prismatic	3D	Prismatic	3D	Prismatic	3D	Radial
ω rad/s	18684.3	18684.3	18684.3	18684.3	18684.3	18684.3	**18684.3**
eff_ts %	69.10	65.80	77.70	77.70	79.30	80.20	**52.71**
eff_tt %	79.80	79.20	82.00	82.50	81.79	82.30	**61.40**
power kW	13.52	12.99	15.45	15.24	15.77	15.14	**6.82**
diameter_hub REF mm	17.66	17.20	26.50	26.50	33.60	33.60	**9.00**
diameter_tip MAX mm	36.97	36.50	46.60	46.50	55.50	55.60	**38.00**
u/c0	0.40	0.39	0.52	0.51	0.58	0.62	**0.91**
Normalized blades inertia	0.622	1.182	2.749	2.709	5.408	3.326	1
Normalized inertia no-opt	0.310	0.495	1.417	1.465	3.058	2.363	1
Normalized inertia pre-opt	0.280	0.474	1.300	1.333	2.762	2.060	1
Normalized Power	1.982	1.905	2.285	2.235	2.312	2.220	1
Normalized mass	0.497	0.545	1.049	1.119	1.614	1.348	1
Normalized eff_ts	1.311	1.248	1.474	1.474	1.504	1.522	1
Normalized eff_ts to inertia ratio	4.229	2.520	1.041	1.006	0.492	0.644	1
Normalized power to inertia ratio	6.395	3.846	1.599	1.526	0.756	0.939	1
Normalized dω/dP	4.229	2.520	1.041	1.006	0.492	0.644	1
Normalized Cost Rotor CNC	0.616	0.781					1
Normalized Cost Rotor+Stator CNC	1.171	1.515					1
Normalized Total dω/dP	1.96	1.59	1.11	1.08	0.66	0.81	1

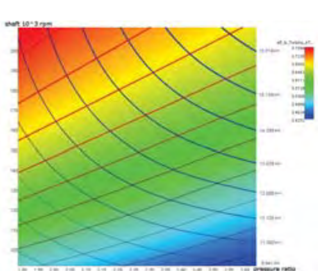
The range 1 prismatic turbine is **96% more responsive than the OEM radial one** to energy rise in the exhaust gases at the design point, meaning that it is able to accelerate quicker and significantly reduce the spool-up time of the turbocharger to the benefit of the engine performance and thus the driving experience.



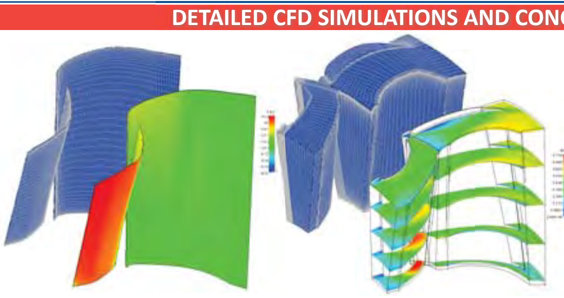
Curvature - Prismatic blade (left) and 3D blade (right)

DETAILED CFD SIMULATIONS AND CONCLUSIONS

Before finalizing the design with CFD and FEA simulations, maps of the turbine were generated with the 2D streamlines solver to investigate the suitability of the turbine for different flow conditions in a short time.



Map of the turbine obtained via streamline analysis

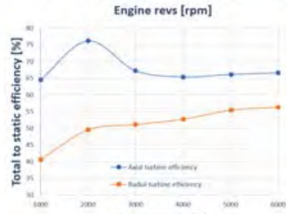


Axisymmetric mesh and pressure scene - 3D HO mesh and Mach contours span-wise scenes

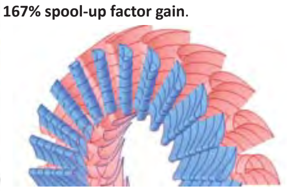
Then, CFD (RANS) simulations of the turbine were performed in AxCFD for several engine flow conditions at full load from 1000rpm to 6000rpm.

Initially, Axisymmetric simulations were conducted to have a faster more precise response about the performance of the machine before concluding the CFD campaign with fully 3D periodic simulations allowing for the most accurate result.

Finally, FEA structural analysis completed the concept design process.



The results of the CFD simulations illustrated in the graphs demonstrate the **superiority of the proposed turbine both from the spool-up factor (dω/dP) and efficiency point of view**, confirming the success of the project. The 17% cost rise for the turbine, which is even less when calculated in respect of the whole turbocharger cost, represents a small price for an **average 167% spool-up factor gain**.



Stator (blue) and rotor (red) view of the turbine

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