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Performance prediction of a nozzled and nozzleless mixed-flow turbine in steady conditions

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ABSTRACT

This paper presents a meanline model to predict the performance parameters of a turbocharger turbine under steady state conditions. The turbine was developed at Imperial College and the design was based on a commercial nozzleless unit that was modified into a variable geometry single-entry turbine.

The wide range of tests data from the Imperial College Turbocharger Group dynamometer enabled the evaluation of the model in the areas of the turbine map where currently no previous comparison had been made in the literature. This facility is designed to allow testing over a wide range of velocity ratios (0.3–1.1) previously unavailable with conventional test stands.

The nozzleless turbine model was validated against experimental results spanning an equivalent speed range of 27.9 and 53.8 rev/s $\sqrt{K}$ while for the nozzled case the model was validated against one single speed (43.0 rev/s $\sqrt{K}$) and three different vane angle settings (40°, 60° and 70°).

The results of the model simulation showed that the performance can be predicted with excellent accuracy for different turbine speeds and vane angles. Based on the model prediction, a breakdown aerodynamic loss was performed.

1. Introduction

Nowadays the more and more stringent limitations in emission regulations in the automotive sector have increased the demand for Exhaust Energy Recovery Systems (EERS). In particular the current trend of pushing towards heavily downsized engines make the EERS essential to the overall economy of a vehicle and its fuel consumption: heat recovery systems, organic rankine cycles and batteries seem to be in vogue as potential future EERS even though their implementation in mass production is still limited to a niche.

Despite being an established technology, turbochargers play a key-role amongst the EERS: costs and size together with improved engine performance make turbochargers the primary choice of car manufacturers. Significant improvements have been made in the design of turbochargers (aerodynamics, materials and bearings reliability have dramatically enhanced over the years) and therefore one of the main challenges in the current research is

(1) tackling issues related with turbocharger performance under pulsating flow conditions and
(2) understanding their impact on the overall engine performance. The implementation of fully unsteady turbocharger models is still far from being achieved due to (1) the complexity of the flow mechanisms occurring within the turbine and (2) the high demand of computational resources, which would be required.

Engine manufacturers commonly use commercial 1-D gas dynamic codes, which have already proven their effectiveness in many respects (combustion, acoustic and emissions) and compare well against experimental results [1]. Commercial turbocharger/engine matching software is developed around the assumption that turbochargers behave in a quasi-steady manner. This implies that the turbine and the compressor behave in a quasi-steady manner in which the enthalpy rise, the mass flow and the torque produced by the turbine are calculated by interpolating a steady state map. Although the quasi-steady assumption is far from being representative of the unsteadiness occurring within a turbocharger and despite there are still ongoing debates on the pertinence of such an approach (which go beyond the scope of this paper), the quasi-steady assumption gains its strength in that it only requires the knowledge of steady state maps, which are usually made available by turbocharger manufacturers since they do not have to disclose geometrical information of their product [1]. However the main drawback associated with these maps is that they are usually narrow in range (due to the limitation of

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Nomenclature

A	area (m^2)
B	blockage factor
C	absolute flow velocity (m/s)
h	height (m)
i	incidence angle
K	loss coefficient
l	length (m)
L	loss
$\dot{m}$	mass flow rate (kg/s)
N	turbine speed (rpm)
MFP	mass flow parameter ((kg/s)$\sqrt{K}$/Pa)
P	pressure (Pa)
PR	pressure ratio
R	universal gas constant (J/kmol)
r	radius (m)
S	swirl
T	temperature (K)
U	rotor velocity (m/s)
VR	velocity ratio
W	relative flow velocity (m/s)
$\dot{W}$	power (W)
Y	RMSD parameter

Greeks

β	relative flow angle (rad)
γ	specific heat ratio
η	efficiency
μ	viscosity (kg/m s)
ρ	density (kg/m^3)
ξ	kinetic energy loss coefficient
σ	entropy gain
Π	mass flow vector

Subscripts

θ	tangential component
act	actual
b	blade
cl	clearance
df	disc friction
inc	incidence
is	isentropic
m	meridional component
opt	optimum
PL	pressure loss
p	passage
$pred$	predicted
ts	total-to-static
0	total conditions
1	inlet to the volute
2	inlet to the rotor
3	exit to the rotor (upstream)
4	exit to the rotor (downstream)

Nozzled turbine

3	exit to the nozzles (upstream)
4	exit to the nozzles (downstream)
5	inlet to the rotor

the conventional test facilities, explained later in this paragraph) and this forces engine software to rely excessively on extrapolation thus affecting the accuracy of engine simulation outcomes. For instance on the turbine side, maps are extrapolated by anchoring them in two points, the first corresponding to zero velocity ratio and efficiency, and the second corresponding to a maximum velocity ratio value obtained as the intersection of the linear extrapolation of a number of second order curves fitting the experimental data. It is apparent that such an approach is simplistic with limited physical insight. It has been experimentally demonstrated [2] that turbine maps exhibit a fair degree of shifting (with respect to the maximum velocity ratio value), which comes as a result of the loss mechanisms occurring within the turbine (refer to Fig. 1). Hence a more accurate method for maps extrapolation should be developed and it is within this context that meanline models attract the interest of engine software developers.

The main advantages of meanline models is that they rely on very few geometrical conditions, require less computational resources than more sophisticated CFD methods and therefore are often used in the first phase of the design to decide whether a certain approach supplies the expected results before fixing the blade geometry. The first studies towards meanline models were made in NASA by Futral and Wasserbauer [3], Glassman and Wasserbauer [4], and later on by Meitner and Glassmann [5] who developed steady state models for nozzled radial turbines. The main structure of their studies is still valid even though the limited number of equations describing the effects of losses inevitably produces a limited performance prediction. Later on Abidat et al. [6] proposed a method to predict the performance in a mixed-flow turbine under both steady and unsteady conditions. Several losses affecting the path of the flow as the blading loss and the skin friction loss were taken into account. Similar to the other model, the code proposed by Abidat et al. [6] proposed a method taking into account several losses affecting the path of the flow, such as the incidence loss, the blading loss and the skin friction loss and solving the one-dimensional fluid dynamic equations at a series of key stations along the turbine path. Finally Qiu and Baines [7] proposed a method for radial turbines keeping into account the throat area at the inlet to the rotor. Although at 100% speed their model seems to show a good prediction at peak efficiency, the validation against experimental data had to rely on

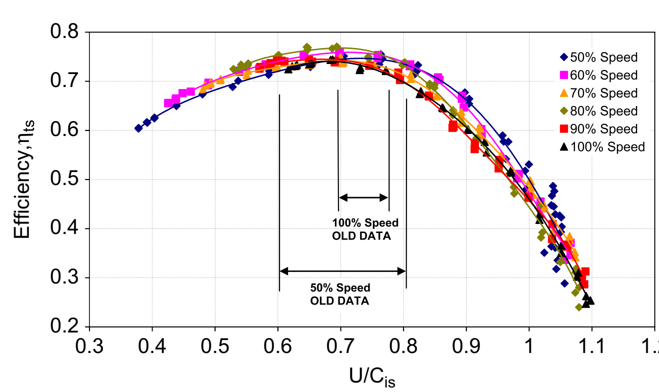

Fig. 1. Efficiency vs. velocity ratio turbine map: comparison between Imperial College and conventional test range (OLD DATA).