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Development and validation of a radial turbine efficiency and mass flow model at design and off-design conditions

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ABSTRACT

Turbine performance at extreme off-design conditions is growing in importance for properly computing turbocharged reciprocating internal combustion engines behaviour during urban driving conditions at current and future homologation cycles. In these cases, the turbine operates at very low flow rates and power outputs and at very high blade to jet speed ratios during transitory periods due to turbocharger wheel inertia and the high pulsation level of engine exhaust flow. This paper presents a physically based method that is able to extrapolate radial turbines reduced mass flow and adiabatic efficiency in blade speed ratio, turbine rotational speed and stator vanes position. The model uses a very narrow range of experimental data from turbine maps to fit the necessary coefficients. By using a special experimental turbocharger gas stand, experimental data have been obtained for extremely low turbine power outputs for the sake of model validation. Even if the data used for fitting only covers the turbine normal operation zone, the extrapolation model provides very good agreement with the experiments at very high blade speed ratio points; producing also good results when extrapolating in rotational speed and stator vanes position.

1. Introduction

In the past years an important increment of interest in improving the prediction of transient and partial load conditions of turbocharged reciprocating internal combustion engines (ICE) has appeared. Due to the strict emission regulations engine manufactures focus engine design in operating conditions different from the traditional full load conditions. As it is showed in [1], during engine transient and partial load design conditions for the ICE the turbocharger turbine works at off-design conditions. In these off-design conditions the turbine works at high blade to jet speed ratios (σ) or low pressure ratios and low power outputs as shown in [2] due to turbocharger wheel inertia and pulsating flow in the exhaust of the ICE. Traditional measurements of turbine maps in gas stands are unable to capture this behaviour [3]. Only a narrow range turbine map is provided by manufacturers as a standard practice. Turbine maps are necessary when using 1D or 0D modelling tools to predict the whole engine behaviour. In 1D modelling approach the one-dimensional unsteady non-homentropic mass, momentum and energy conservation laws (Euler equations) are solved. Specific source terms are used to simulate the friction and heat exchange in the pipes. The 1D simulation codes make possible the calculation of gas dynamics engine behaviour at low computational costs. Some engine components are modelled with a 0D approach, using specific lumped parameter models or performance maps. That is the case of cylinders, injectors, valves, compressors and turbines which are coupled to the 1D computational domain as it is described in [4]. For that reason, turbocharged ICE designers must rely on map extrapolation tools when predicting engine performance outside of turbine design operative conditions [5]. It is typical in pulsating flow conditions, requiring different modelling approaches similar to the proposed in [6], where meanline one-dimensional models are discussed and in [7], where non-adiabatic pressure loss boundary condition is discussed. One-dimensional tools are also used in design process for fast evaluation of turbine capabilities as in [8]. In [9] a Taylor series expansion is used to develop a model able of predicting mass flow parameter of radial turbines.

CFD models for turbine design have been developed in [10]. This approach is useful when turbine CAD files are ready. However, this

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Nomenclature

A	area (m^2)
a	rotor discharge coefficient (–)
b	reduced mass flow fitting coefficient (–)
c	reduced mass flow fitting coefficient (–)
C_D	discharge coefficient (–)
c_{ss}	isentropic jet velocity (ms^{-1})
c_p	specific heat capacity at constant pressure ($J\,K^{-1}$)
D	diameter (m)
d	reduced mass flow fitting coefficient (–)
K	efficiency equation coefficient (–)
L	length (m)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
$\dot{m}_{red}$	reduced mass flow rate ($kg\,K^{1/2}\,s^{-1}\,bar^{-1}$)
n	rotational speed (rpm)
n_{red}	reduced rotational speed ($rpm\,K^{-1/2}$)
n_b	number of blades (–)
p	pressure (Pa)
R	perfect gas constant ($J\,kg^{-1}\,K^{-1}$)
r	rotor radius (m)
sd	standard deviation (–)
sp	spacing between stator blades (m)
t	blades and/or channel width (m)
T	temperature (K)
$\dot{Q}$	heat flux (W)
u	blade tip speed (ms^{-1})
v	absolute velocity (ms^{-1})
VGT	VGT position (%)
$\dot{W}$	power (W)
w	relative velocity (ms^{-1})

Greek symbols

α	absolute velocity angle (rad)
β	relative velocity angle (rad)
γ	specific heat capacities ratio (–)
δ	angle between consecutive stator blades (rad)
η	efficiency (–)
θ	tangential velocity component (ms^{-1})
Π	pressure ratio (–)
ρ	density ($kg\,m^{-3}$)
σ	blade to jet speed ratio (–)
φ	angle of the stator vanes (rad)

Subsripts and superscripts

0	turbine inlet station
1	stator inlet station
2	stator outlet station
2′	stator throat station
2*a*	stator vanes axis of rotation station
3	rotor inlet station
4	rotor outlet station
geom	refers to geometry
metal	refers to metal angle
Neq	refers to equivalent nozzle
red	refers to reduced variables
s	isentropic conditions and stator
t	total conditions
T	refers to turbine
TE	distance between stator blades axis of rotation and trailing edge
th	refers to throat
ts	total to static
$\bar{}$	average value

Acronyms

VGT	variable geometry turbine
FGT	fixed geometry turbine
ICE	internal combustion engine

information is not always available for automotive engines simulation. Full three-dimensional simulations can reproduce turbocharger behaviour only at a very high computational cost [11] what means that these simulations are only performed at few operating points [12]. Therefore, for whole driving cycle simulations, 1D or 0D approaches must be used to keep low computational costs and an adequate precision.

In the last years, several proposals have appeared in the literature regarding this topic. Some of them are based on pure theoretical approaches [13] but use parameters in losses models that have not been proved to be general on a wide range of turbine sizes or VGT (variable geometry turbine) positions. The same can be said from [6] for adiabatic and from [7] for non-adiabatic turbines modelling. Other models are based on physical considerations but use empirical parameters for fitting stator outlet flow angles, without a clear correlation against physical values of average flow angles [14]. Furthermore, the model proposed in [14] relies on tangent functions, which are mathematically unstable during fitting procedures using numerical methods. Moreover, the model shown in [14] was only validated for blade to jet speed ratio extrapolation, not for turbocharger speed or VGT position extrapolation. Some models in the literature are based on the characterisation of the different losses of the turbine [15] such as passage losses or tip clearance losses [16] but no general procedure for coefficients fitting or a comprehensive model validation at highly off-design conditions have been reported yet. Other models are purely empirical and use the information of the map to fit coefficients as has been done in [17] for SI and DI engines control. A similar approach has been used in [18] for automotive engines simulation, also with a control oriented objective. A review of the advantages and disadvantages of each kind of model has been performed in [19].

As any extrapolation tool, the extrapolation models have always faced an important validation problem. The validity of the modelling can be checked for the measured conditions but not in the outside area, where it is really interesting to use the model. To overcome this problem, special tests have been designed in a gas stand to measure a turbine outside of its design range, at extremely high σ [20]. This new approach provides wider σ range than using a closed circuit in the compressor to extended the operational range of the turbine [21].

In the present paper, a model for turbine characteristics extrapolation is presented. The developed model is suitable to be used in 1D and 0D control oriented simulation codes. The model is capable of extrapolating to non measured VGT positions and reduced speeds. Furthermore, it has been developed based on a database of measured turbochargers and it has been validated in a high σ range by using experimental results from special gas stand tests [20].

The main differences between the model proposed in this paper and literature models lies in the enhanced extrapolation capabilities, the generality and the low quantity of input data needed. The proposed model is able to extrapolate to non-measured VGT position maps, to non-measured reduced speeds and to non-measured blade to jet speed ratios both mass flow parameter