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Integration of meanline and one-dimensional methods for prediction of pulsating performance of a turbocharger turbine

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ABSTRACT

Stringent emission regulations are driving engine manufacturers to increase investment into enabling technologies to achieve better specific fuel consumption, thermal efficiency and most importantly carbon reduction. Engine downsizing is seen as a key enabler to successfully achieve all of these requirements. Boosting through turbocharging is widely regarded as one of the most promising technologies for engine downsizing. However, the wide range of engine speeds and loads requires enhanced quality of engine-turbocharger matching, compared to the conventional approach which considers only the full load condition. Thus, development of computational models capable of predicting the unsteady behaviour of a turbocharger turbine is crucial to the overall matching process. A purely one-dimensional (1D) turbine model is capable of good unsteady swallowing capacity predictions, however it has not been fully exploited to predict instantaneous turbine power. On the contrary, meanline models (zero-dimensional) are regarded as a good tool to determine turbine efficiency in steady state but they do not include any information about the pressure wave action occurring within the turbine.

This paper explores an alternative methodology to predict instantaneous turbine power and swallowing capacity by integrating one-dimensional and meanline models. A single entry mixed-flow turbine is modelled using a 1D gas dynamic code to solve the unsteady flow state in the volute, consequently used as the input for a meanline model to evaluate the instantaneous turbine power. The key in the effectiveness of this methodology relies on the synchronisation of the flow information of different time scales. The model is validated against experimental data generated at Imperial College London under steady and pulsating flow conditions. Three rotational speeds (27.0, 43.0, and 53.7 rps/$\sqrt{K}$) and four pulse flow frequencies (20 to 80 Hz) are considered for performance validation. In addition to the turbine performance, the common level of unsteadiness is also compared based on Strouhal number evaluations. Furthermore, comparisons are made with the quasi-steady assumption in order to understand the strengths and weaknesses of the current method for effective unsteady turbine performance prediction.

1. Introduction

Stringent emission regulations are currently propelling the automotive sector towards alternative powertrain designs [1]. However, despite the huge investments in different powertrains, internal combustion engines are expected to remain as the mainstream choice in the automotive industry. This is mainly due to a better cost/benefit ratio in terms of emission reduction technologies [2]. Engine downsizing, in conjunction with exhaust energy recovery systems and boosting technologies (turbocharging, supercharging, electric turbocompounding, etc.), is recognised as an efficient way of cutting down CO_2 emissions [3]. In the last few years, the implementation of downsizing technology in diesel engines has shown great success in significantly reducing CO_2 emissions, by as much as 30–40%. Therefore it is anticipated that gasoline engine development will catch up to a similar trend in the years to come [4].

In order to deliver novel and cost effective solutions, engine developers are increasingly relying on 1D engine simulation software. Despite being widely used during the development stage of a turbocharged engine, for instance engine-turbocharger matching, these models are not fully representative of the engine thermal and fluid dynamics and therefore need a significant amount of calibration. In fact, the mismatch usually encountered between

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Nomenclature

a	speed of sound (m/s)
C	rotor velocity component (m/s)
F	cross-sectional area (m^2)
f	wave frequency (Hz)
l	characteristic length (m)
MFP	pseudo-non-dimensional mass flow parameter
MSt	modified Strouhal number
$\dot{m}$	mass flow rate (kg/s)
N	rotor rotational speed (rps)
PMSt	pressure modified Strouhal number
p	pressure (bar)
r	radius (m)
T	temperature (K)
u	gas velocity (m/s)
U	rotor tangential velocity (m/s)
$\dot{W}$	power (kW)
W	rotor relative velocity (m/s)

Greek symbols

α	absolute flow angle (rad)
β	relative flow angle (rad)
ϕ	pulse period fraction
θ	tangential component

Subscripts

0	stagnation state
1	at measurement plane
2	at turbine tongue
3	at rotor upstream
4	at rotor downstream
act	actual
exp	experimental
m	meridional component
max	maximum
pred	prediction

the engine test data and simulation results is one of the main drivers forcing engine developers to look into novel methodologies to refine model predictions. This is particularly true for turbocharger turbines which are still modelled as steady flow devices without taking into account the gas dynamics due to the pulsating nature of the exhaust gas flow. It is therefore the aim of this paper to contribute in providing an insight towards a novel modelling methodology for turbocharger turbines.

1.1. Background study

Several turbine modelling methods have been developed over the years, each having different levels of complexity and capability. In general, these models can be categorised according to the number of spatial dimensions employed, ranging from zero to three-dimensions.

Three-dimensional (3D) modelling approach provides the most comprehensive representation of the flow dynamics occurring within the turbine, allowing a detailed study of the energy propagation along the volute, the secondary flow phenomena, and the interaction between the rotor and gas flow [5–9]. Such an accurate level of analysis enables the optimisation of the turbine design to achieve better performance [10,11]. On the other hand, the main drawback for 3D modelling is in its demand for time, cost, and computational resources. This does not make it a favourable option in situations where a large number of simulations might be required.

A valid alternative solution could therefore be much simpler 1D modelling that focuses on the variation of the flow parameters along the single spatial dimension of the system in which the flow experiences the largest changes in energy. For turbocharger turbines, this refers to the direction of the mean flow path for the volute and the meridional direction for the rotor. Such an approach effectively decreases the mesh densities and the computational time compared to an equivalent 3D model. However in order to maintain an adequate prediction quality, the simplifications in 1D modelling are compensated by the use of more extensive boundary conditions, which typically rely on empirical correlations. One-dimensional modelling is widely used in engine manifold tuning [12,13], exhaust gas recirculation architecture design [14], engine transient response [15] and emissions studies [16], due to its superior ability in capturing the wave action in the model domain in a reasonable time, compared to its 3D counterpart. On the other hand, current 1D models fall short when trying to replicate the turbine since they are almost universally reliant on steady flow hot gas bench test data, known as turbocharger maps. Due to the test method normally employed, the turbine map in particular requires extensive extrapolation before it can be used in simulation. Furthermore, its validity in a highly unsteady flow is questionable, especially for twin scroll turbines, which are increasingly applied to passenger car engines to enhance torque at low engine speeds and thereby improve transient response.

Another simpler yet powerful modelling methodology is 0D modelling, typically known as mean-value or meanline modelling in the turbomachinery field. Mean-value engine modelling has been extensively used in preliminary engine simulation since the early 60's [17] and remains popular today [18,19]. Likewise, meanline models are regularly used in the preliminary turbomachine design phase to analyse turbine (and compressor) steady flow performance. Meanline models assume the flow conditions remain constant over time and rely on empirical correlations to evaluate the aerodynamic losses. Thus the major drawback of a meanline model lies in its zero-dimensional nature which makes it unable to account for any temporal variation of the pulsating flow conditions typical of a real turbocharger turbine.

The Strouhal number, St, analysis in [20] showed the unsteady nature of the flow going through the turbine rotor can be neglected due to the short rotor passage length relative to the typical exhaust flow frequency. This is not the case in the turbine volute due to the much longer time taken by the gas to travel from the turbine inlet to the rotor. The quasi-steady nature of the flow in the turbine rotor was further investigated in [21] where results showed that over a pulse cycle the flow velocity entering the rotor has the same magnitude and direction as that which would be attained in a steady flow of similar properties.

As mentioned earlier, the main downside of a 1D engine simulation is that the turbine stage (volute and rotor) is modelled as a boundary condition (hence imposing the quasi-steady assumption). Hence at each computational time step, the turbine mass flow and efficiency values are obtained from the steady state turbine performance maps[1] according to turbine inlet flow conditions [22]. However, assuming quasi-steady behaviour throughout the turbine stage is not an ideal representation since the volute is

[1] Turbine performance maps are generated from experimental tests conducted by turbocharger manufacturers.