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An investigation on unsteadiness of a mixed-flow turbine under pulsating conditions

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ABSTRACT

The turbocharger is the key enabler for energy conservation in Internal Combustion Engine (ICE). A turbine of a turbocharger is fed by highly pulsating flow due to the reciprocating engine, resulting in different behavior from that at steady conditions. This paper investigates the behavior of a mix-flow turbine under pulsating conditions via an analytical model and an in-house developed 1-D unsteady code ***ONDAS***. Firstly, an analytical model of the 'unsteadiness' based on the mass flow imbalance is built and the mechanism of the unsteady behavior is discussed in details. Next, a 1-D unsteady model of the turbine under pulsating conditions is established and validated by experimental results. Finally, influence of the frequency, the magnitude and their product on unsteady behavior of the turbine is investigated by the reduced order model for further exploration of the analytical model. The investigation clearly demonstrates the impact of pulsating flow on the unsteady performance and unveils the mechanism of the 'unsteadiness' of turbine under pulsating conditions.

1. Introduction

The increasing demand of low carbon vehicle has forced the industry toward highly efficient and downsized engines. One of the key enablers to produce a high specific power engine is the turbocharger which boosts the intake air for the combustion of more fuel. Furthermore, the turbocharger is also applied for exhaust energy recovery in Internal Combustion Engine [1]. A turbine is the component of energy claiming in the turbocharger and hence attracts extensive researches. The matching between the turbine and the engine is essential for the performance of a turbocharged engine. For instance, the swallowing capacity of a turbine has to be matched properly with the breathing characteristic of an engine to guarantee the optimization of engine performance. Usually the performance of a turbine applied for the turbo-engine matching, including swallowing capacity and efficiency, is obtained from the turbocharger test at steady conditions [2,3]. However, a turbocharger turbine is confronted by highly pulsating flow because of the interval opening of the valve of cylinders. The pulsating conditions result in the turbine behavior which deviates from that at steady conditions [4,5].

Comprehensive investigations have been performed on the unsteady behavior of turbine under pulsating conditions. Kosuge and Wallace have carried out pioneering investigations of the turbine performance under pulsating conditions [5,6]. It was found that the swallowing capacity and the output power of the turbine reduced notably under pulsating conditions. Indexes of the averaged performance over a pulse period were introduced for evaluation of the pulsating effect. The frequency and the shape of a pulse were considered to be main factors of the influence. A parameter which combines the influence of the pulse frequency and its magnitude to quantify the effect was suggested. But as authors pointed out, the accuracy of the test could not be guaranteed due to lack of the reliable test facilities. Baines and Capobianco [7,8] experimentally investigated the influence of pulsation on turbine behavior and further confirmed the effect on the performance. Imperial College London investigated the influence of the pulsation on a mix-flow turbine via the experimental method and the distinctions among different configurations have been solidly demonstrated [9–11]. With the long-term-developed test apparatus, Copeland experimentally compared performance of a double-entry turbine under pulsating conditions with the one at steady conditions [12]. The degradation of the performance with the frequency was demonstrated.

In order to quantify the unsteadiness of the turbine under pulsating conditions, several parameters were introduced in

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Nomenclature

A	area (mm^2)
f	frequency (Hz)
f_c	friction coefficient (–)
j	imaginary unit (–)
l	characteristic length (mm)
M	dimensionless magnitude (–)
MFP	mass flow rate parameter $MFP = \frac{\dot{m}\sqrt{T}}{P}$ (kg/s $\sqrt{\text{K}}$/Pa)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
PR	pressure ratio (–)
St	Strouhal number (–)
T	period of pulse (s)
TVD	total variables diminish
t	time (s)
u	velocity (m/s)

Greek letters

α	sonic speed (m/s)
ϕ	relative mass flow rate parameter (–)
ψ	mass imbalance parameter (–)
ω	round frequency (rad/s)
ρ	density (kg/m^3)

Subscripts

ave	average
ex	exit
in	inlet
n	the *n*th component of Fourier series
s	static
t	total

researches. The Strouhal number (St), defined by the characteristic length l, velocity U and perturbation frequency f $\left(St = \frac{f \cdot l}{U}\right)$, is the most widely employed dimensionless parameter to for the evaluation. Specifically, for the unsteadiness of a turbine confronted by pulsating conditions, the bulk flow velocity plus the sonic speed are employed as the characteristic velocity; the pulse frequency is applied as the characteristic frequency; the length for the propagation of the perturbation is the characteristic length. In order to consider the effect of pulse shape on turbine unsteadiness, Karamaris and Costall further corrected the definition of the number by introducing a shape coefficient [13,14] (named as 'corrected Strouhal number'). By studying the filling and emptying process in a twin-entry turbine under pulsating conditions, Copeland suggested a new parameter to include the effect of both pulse frequency and the pulse magnitude [15]. The mass accumulation in a reservoir was modeled and found out be determined by pulse magnitude and frequency. It is the first time that the mass accumulation is theoretically linked with pulse parameters for a turbocharger turbine under pulsation. The mass flow imbalance, which is the difference of the mass flow rate at the inlet and the exit of the turbine at an instant time, is considered to be a reasonable indicator of the turbine unsteadiness [15–17]. The validation of the parameter for the unsteadiness evaluation has been numerically commenced by Padzillah et al. [18]. The new parameter is further confirmed by checking the response of a turbine rotor under different pulsating conditions [19,20]. In the study, the deviation from the steady performance was applied for the indication of 'grade of unsteadiness'. Impressively, the conclusion turned out to be similar as the one suggested in Ref. [15]. Furthermore, the deduction in the investigation confirmed that it is the local gradient of the pressure pulse that determines the unsteady behavior of the turbine. More deep insights of the influence on the turbine unsteadiness under pulsation need to be further explored.

Experimental measurement and unsteady 3-D CFD are main methods for the investigations of unsteadiness in a turbine under pulsation. It is quite a challenge for reliable measurement of the turbine performance under pulsating conditions, especially for the measurement of the instant output/input power. Actually until recent years experimental results with the satisfied validation with CFD prediction have been reported [21–23]. On the other hand, the full stage unsteady 3-D CFD costs tremendous computational resources due to different time scales between pulsation and turbine rotation, regardless of lack of reliable validation data from tests. It is impractical to perform an investigation on the influence of pulsation on turbine unsteady behavior covering wide range of pulsating conditions via full-stage 3-D unsteady CFD, unless the model is heavily simplified or the complexity is order-reduced [20]. On the other hand, Costall, Chiong, and Yang investigated the unsteady performance via an in-house developed 1-D unsteady code. The reliability of the reduced order method was confirmed for the prediction of the turbine unsteadiness under pulsating conditions [24–27].

In this paper, the influence of pulsating conditions on turbine unsteadiness is studied by reduced order models, including an analytical model based on the 1-D momentum equation and a 1-D unsteady model via the 1-D unsteady code ***ONDAS***. The study provides a further insight to the influence of pulsation on turbine unsteadiness.

2. Analytical model of mass imbalance

A hysteresis loop of swallowing capacity, which is caused by flow imbalanced in the turbine, is recognized as a typical sign of unsteadiness of a turbine under pulsating conditions because of its deviation from the steady characteristics. A schematic of mass flow imbalance for a turbine under pulsating condition is shown in Fig. 1. The difference of mass flow rate between the hysteresis loop and the steady curve at a pressure ratio is approximately the same as the mass flow imbalance at the corresponding condition in a pulse. Therefore, it is reasonable to evaluate the 'grade of

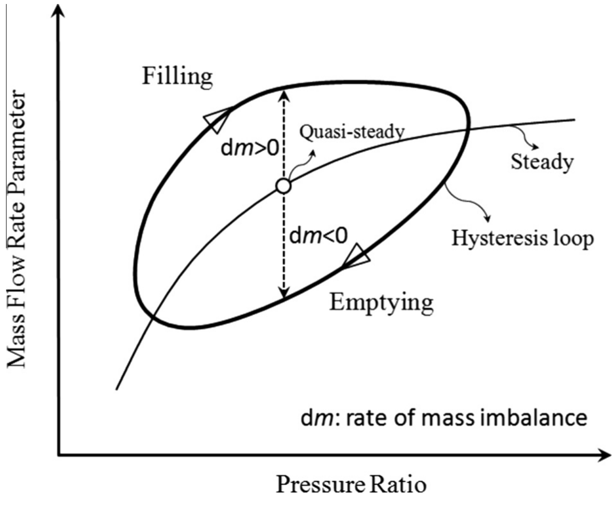

Fig. 1. Schematic of mass flow imbalance in a turbine under a pulsating condition.