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Influence of tip clearance on flow behavior and noise generation of centrifugal compressors in near-surge conditions

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ABSTRACT

CFD has become an essential tool for researchers to analyze centrifugal compressors. Tip leakage flow is usually considered one of the main mechanisms that dictate compressor flow field and stability. However, it is a common practice to rely on CAD tip clearance, even though the gap between blades and shroud changes when compressor is running. In this paper, sensitivity of centrifugal compressor flow field and noise prediction to tip clearance ratio is investigated. 3D CFD simulations are performed with three different tip clearance ratios in accordance to expected operating values, extracted from shaft motion measurements and FEM predictions of temperature and rotational deformation. Near-surge operating conditions are simulated with URANS and DES. DES shows superior performance for acoustic predictions. Cases with reduced tip clearance present higher pressure ratio and isentropic efficiency, but no significant changes in compressor acoustic signature are found when varying clearance. In this working point, tip clearance is immersed in a region of strongly swirling backflow. Therefore, tip leakage cannot establish any coherent noise source mechanism.

1. Introduction

Turbochargers are present in almost all diesel engines and its use in gasoline engines has been steadily increasing in the last years. Turbocharging allows reductions of engine displacement and weight without reducing the power and torque produced, in a trend known as downsizing. This approach reduces fuel consumption and emissions, which is a must for successfully fulfilling the current regulations.

Yet strongly downsizing of engines and increase of low speed torque raises an issue with turbocharger airborne noise (Evans and Ward, 2005), since compressor operating points are shifted towards surge region (Teng and Homco, 2009).

Leakage flow from blade PS to SS across tip clearance is often considered as a key point in the stability and noise production of centrifugal compressors. Raitor and Neise (2008) conducted an experimental study to analyze the sound generation mechanisms of centrifugal compressors. Tip clearance noise (TCN) predominates over BPF tone for subsonic flow conditions at low compressor speeds. TCN is a narrow-band noise observed at frequencies about half the blade passing frequency (BPF), which increase with speed. Raitor and Neise considered that secondary flow through blade tip clearance is the source of TCN.

In this frame, CFD is a tool used by researchers to investigate centrifugal compressor flow field and particularly tip leakage flow. Mendonça et al. (2012) analyzed flow-induced aeroacoustics of an automotive radial compressor using DES. A narrow band noise at a frequency about 70% of rotational speed was detected. Rotating stall was found to be the source of the narrow band noise. Tip leakage allows the stalled passages to recover by pushing the low momentum region to the rotation-trailing passage, according to Mendonça et al.

Tomita et al. (2013) studied two compressors with similar map except in surge vicinity. Unsteady pressure measurements performed just upstream the impeller leading edge at low mass flow rate revealed differences between compressors: the one with the narrowest operating range showed large pressure fluctuations at subsynchronous speeds moving circumferentially at about 50–80% of compressor speed, whereas compressor with wide operating range did not exhibit this large amplitude fluctuations. 3D CFD numerical simulations were also performed in order to analyze fluid phenomena at this low mass flow rate conditions. Compressor with less surge margin presented a tornado-type vortex between blades, blocking the incoming flow. This vortex is convected downstream and a new one is created in the adjacent blade, in a rotating stall pattern. Conversely, spiral-type tip leakage

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Nomenclature

List of symbols

a	speed of sound (m s^{-1})
c_p	specific heat capacity at constant pressure (J kg^{-1} - K^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
N	compressor rotational speed (rpm)
p	pressure (Pa)
t	time (s)
T	temperature (K)
u	axial velocity (m s^{-1})
$\dot{W}$	compressor absorbed power (kg m^2 s^{-3})
W_u	compressor specific work (m^2 s^{-2})
η	efficiency (%)
ϵ	relative difference (%)
γ	ratio of specific heats (–)
ϕ	generic variable
$\Pi_{t,t}$	total-to-total pressure ratio (–)
τ	compressor torque (kg m^2 s^{-2})

Sub- and superscripts

$*$	corrected variable
0	stagnation variable
1/3, 2/3, 3/3	related to one third, two thirds or three thirds of original clearance, respectively
back	backward traveling wave
CFD	related to simulation
exp	related to experimental measurement
in	inlet duct
forw	forward traveling wave
out	outlet duct
s	isentropic
ref	reference value

List of abbreviations

BPF	blade passing frequency
CAD	computer-aided design
CFD	computational fluid dynamics
DDES	delayed DES
DES	Detached Eddy Simulation
FEM	finite element method
IDDES	improved DDES
LES	Large Eddy Simulation
LIC	Line Integral Convolution
MoC	Method of Characteristics
PS	(blade) pressure side
PSD	power spectral density
RANS	Reynolds-averaged Navier–Stokes
TCN	tip clearance noise
TCR	tip clearance ratio
SS	(blade) suction side
URANS	Unsteady RANS
WMLES	wall-modeled LES

vortex breakdown occurred at all blades for compressor with higher surge margin. Some rotating instability was observed in this compressor, but not as severe as the rotating stall experienced as in the other compressor. Tomita et al. (2013) concluded that tip leakage vortex breakdown could stabilize the flow structure and thus increase surge margin.

Increased computational resources have made possible to include tip clearance in most of the current CFD simulations of centrifugal compressor (Mendonça et al., 2012; Tomita et al., 2013). However, compressor geometry is often obtained from reverse engineering or manufacturer's CAD, thus modeling a *cold* tip clearance that is not representative of actual working conditions. Deformations due to temperature, rotation or pressure are usually neglected, and shaft motion is not considered. Including these effects will led to coupled fluid–structure simulations, which are very expensive. Nevertheless, the effect of these factors should be studied to assess the validity of simulations using CAD clearance.

Many researchers have performed studies of tip clearance sensitivity on global variables and local flow features.

Danish et al. (2006) conducted a numerical study in which overall performance and flow field were investigated for nine tip clearance levels from no gap to 16% tip clearance ratio (TCR). Numerical simulations were performed with frozen rotor technique. Two different clearance increase approaches were used: reduction of blade height while keeping same housing dimensions and increase of shroud diameter with same blade height. For operating conditions close to best efficiency point, maximum increase of TCR by decrease of blade height caused a loss of 15% in pressure ratio and 10% in efficiency. If shroud size is increased instead, pressure ratio is reduced by 13% and efficiency by 8.5%.

Jung et al. (2012) performed steady simulations using the same impeller with six different tip clearance profiles. Reductions in tip clearance caused an increase in pressure ratio and efficiency. Particularly, a decrease in tip clearance at the trailing edge improved the compressor performance more than implementing the same reduction in leading edge tip clearance. A reduced tip leakage flow was found to significantly improve the diffusion process downstream the impeller.

Measurements performed by Wang et al. (2011) indicated that variations of tip clearance caused small influence on stall inception. However, the reasons could not be investigated because their mixing-plane, steady simulations failed to converge at near surge conditions.

However, in these sensitivity studies, particular TCRs are not usually justified by expected values of compressor actual working conditions and effect on noise generation is not assessed.

According to the literature review, tip leakage flow may play a role in noise generation and stability of centrifugal compressors. CFD can provide a deeper insight into the issue, but clearance sensitivity to noise generation must be first assessed to decide if clearance variations from baseline CAD conditions can be safely neglected. In such a sensitivity study, TCRs should be set in accordance to expected values while compressor is operating.

In this paper, the effect of tip clearance size on fluid flow and noise spectra of a 49 mm exducer diameter turbocharger compressor is studied. Section 2 is devoted to the estimation of tip clearance reduction during actual compressor operation. In Section 3, the numerical set-up is described and the approach to perform the clearance sensitivity analysis is explained. Tip clearance size impact on global variables and noise generation is evaluated in Section 4 by means of PSD comparison. Flow field is investigated in Section 5 in order to explain the spectra obtained by different TCRs. Finally, Section 6 includes the main findings of the paper.

2. Estimation of actual tip clearance

In Section 1, some effects usually not considered when simulating turbocharger compressors were introduced. For the sake of accuracy, a two-way coupled fluid–structure simulation should be