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Investigation of turbocharger compressor surge inception by means of an acoustic two-port model

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ABSTRACT

The use of centrifugal compressors have increased tremendously in the last decade being implemented in the modern IC engine design as a key component. However, an efficient implementation is restricted by the compression system surge phenomenon. The focus in the investigation of surge inception have mainly been on the aerodynamic field while neglecting the acoustic field. In the present work a new method based on the full acoustic 2-port model is proposed for investigation of centrifugal compressor stall and surge inception. Essentially, the compressor is acoustically decoupled from the compression system, hence enabling the determination of sound generation and the quantification of internal aero-acoustic coupling effects, both independently of the connected pipe system. These frequency dependent quantities are indicating if the compressor is prone to self-sustained oscillations in case of positive feedback when installed in a system. The method is demonstrated on experimentally determined 2-port data of an automotive turbocharger centrifugal compressor under a variety of realistic operating conditions.

1. Introduction

In order to comply with the European Commission Euro 6 emission standard [1], while maintaining the original power output, the concept of engine downsizing (or "rightsizing") have been introduced and widely implemented by the passenger car industry (See e.g. Refs. [2–5]). Essentially, the volumetric capacity of the IC engine have been decreased while increasing charge air density, thus leading to a significantly better fuel conversion efficiency with low penalty of NO_x emissions. The key component in the concept is a turbocharger that increases the charge air density by means of recovered energy from the high enthalpy exhaust gas. Typically the turbocharger consists of a radial in-flow turbine, and of a centrifugal compressor that are integrated to the gas exchange system of the IC engine.

Substantial challenges related to downsized IC engines involve compressor noise, insufficient mass flow range of the compressor, and reduced transient response. With even more stringent Euro 6c emission standard entering to force in September 2018 [6], consequently requiring further downsizing, these challenges become even more relevant. A recent technology addressing these problems is referred to as 48 V e-boost [7]. Essentially, an additional electric motor driven centrifugal compressor will be added downstream [8] or upstream [9] of the turbocharger compressor. Although such

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Nomenclature

$\mathbf{E}$	2 by 2 unit matrix
G	single sided cross-spectra
H	frequency response function
L	level
M	mean flow Mach number
P	acoustic power, W
R	acoustic reflection coefficient
$\mathbf{R}$	the reflection matrix of test rig terminations
$\mathbf{S}$	acoustic scattering matrix
T	acoustic transmission coefficient
$\mathbf{T}$	acoustic transformation matrix
T^{C}	absolute temperature, °K
c	the speed of sound, m s^{-1}
e	external excitation signal, V
f	frequency, s^{-1}
i	unit imaginary number ($i^2 = -1$)
k	wave number, m^{-1}
p	acoustic pressure, Pa
$\mathbf{p}$	1D vector of acoustic pressures, Pa
p^{C}	quasi-static pressure, Pa
t	time, s
t^{C}	temperature, °C
x	axial co-ordinate, m
$\mathbf{x}$	1D vector of axial co-ordinates, m
λ	eigenvalue
ω	angular frequency, s^{-1}

Sub- and superscripts

P	acoustic power
a	compressor inlet port
b	compressor outlet port
i	input
j	microphone number
o	output
p	acoustic pressure
s	acoustic source
0	fluid at rest
†	Hermitian transpose

configuration provides many benefits, the fundamental problem of insignificant mass flow range remains and limits the efficient use of centrifugal compressors.

The maximum mass flow of the centrifugal compressor is determined by a choked flow, while the minimum stable mass flow is bounded by the inception of surge phenomenon. When the back pressure of the coupled system becomes too high, the compressor cannot maintain continuous discharge pressure and a local flow reversal occur. This leads to global self-sustained large amplitude pressure and mass flow oscillations across the entire compression system, making surge a system phenomenon [10–12]. The main focus in the surge investigation has been on the inception process and a root cause of surge occurrence. However, as many different static and dynamic stall scenarios can occur and lead to different types of instable operation, the investigation has proved to be challenging.

In 1976 Greitzer proposed a lumped parameter model for investigation of axial compression system instability [13]. This model was validated on centrifugal compressors by Hansen in 1981 [14]. From this model, it is apparent, that the low mass flow instability in the compression system should occur at the Helmholtz frequency of the system. A global pressure and mass flow oscillations approximately corresponding to the Helmholtz frequency of the compression system have also been observed in a number of different experiments (See e.g. Refs. [15–17]). Moreover, the oscillations are appearing to be of progressive type respect to the mass flow reduction, and can grow to relatively large amplitudes eventually causing the blow-down of coupled high pressure discharge volume [15]. However, it has been also observed that the oscillations remain