Measurement 59 (2015) 363–371

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Uncertainties in power computations in a turbocharger test bench

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ARTICLE INFO

Article history:
Received 30 September 2013
Received in revised form 16 September 2014
Accepted 19 September 2014
Available online 7 October 2014

Keywords:
Turbocharger
Uncertainties
Optimisation

ABSTRACT

A specific study of the uncertainties of turbine power output measured in turbocharger test benches is presented using the law of uncertainty propagation and the influence of the different terms that contribute to it is shown. Then, non-linear mixed integer mathematical programming algorithms used with the turbine power uncertainty expression become an essential tool to overcome the problem of selection new sensors to improve an existing test rig or to contribute to a new one. A method of optimisation is presented for two different scenarios: first, where the maximum cost is a constraint; second where the maximum uncertainty is a constraint and the total cost is minimised. When using a large transducers database, computational efforts may be reduced by solving the relaxed non-integer problem by means of sequential quadratic programming and then probing the ceilings and floors of the parameters to get an optimum approximation with low costs. A comparison between the linear uncertainty propagation model and Monte Carlo simulations is also presented, only showing benefits of the later method when computing high order statistical moments of the turbine power output probability distribution.

1. Introduction

Improving the experimental characterisation of centrifugal compressors and centripetal turbines is a topic of high interest for both researchers and engine manufacturers. To ensure minimum errors in the experimental studies done in turbocharger test rigs, experimental measurement standards [1,2] are developed and a high technical knowledge and experience in this particular area is needed, as well as high quality experimental facilities. Nevertheless, as both researchers and engine manufacturers are interested into getting experimental results at operating conditions typical of urban driving cycles, the uncertainty of the measurements done within these experimental facilities becomes excessively high for practical purposes and the test rig designer needs to invest in newer equipment.

Although the uncertainty value of every single sensor in a common test rig is generally small, the number of sensors used in such facilities tends to be numerous, each one contributing to the generation of the final uncertainty of the different quantities of interest. The quantification of these uncertainties requires a separate study of parameters such as air temperature, pressure and mass flow and the characteristics of the transducers used to measure them as seen in different works like [3] or [4].

This work shows the variability of the uncertainty, which is studied statistically, as a function of the type of sensors used: thermocouples and resistance temperature detectors used to measure temperature, pressure sensors like piezoelectric and piezoresistive to measure pressure or the air mass flow measured with a hot wire, vortex flowmeter or rotameter. The propagated uncertainty is computed using a first order Taylor expansion of the

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http://dx.doi.org/10.1016/j.measurement.2014.09.055
0263-2241/

Nomenclature

Symbols

A	duct area
c	speed
c_p	specific heat capacity
d	cost
e	recovery factor
G	geometric mean
$\dot{m}$	mass flow rate
N	maximum allowable number of sensors
p	pressure
H	Heavyside's step function
R	gas constant
T	temperature
$\widehat{T}$	measured temperature
u	uncertainty
$\dot{W}_T$	turbine power
Y	specific humidity
γ	specific heat capacity ratio
k	coverage factor
x	measured quantity
y	number of sensors of a given type
z	derived quantity

Subscripts

3	turbine inlet
4	turbine outlet
0	stagnation quantity
initial	initial quantity
M	maximum quantity
mean	mean quantity
s	available in stock

expressions of interest, then computing the variance–covariance matrix of the obtained linear approximation and neglecting the covariance terms due to lack of correlation between the different variables, and assuming normal distribution of the final results. While there are several papers about turbocharger experimental studies with uncertainties computations done in detail, like in [5], it is usually not the case. The aim of this work is the development of a flexible methodology to estimate the measurement uncertainties in the particular case of the experimental characterisation of turbochargers and to give hints to the test rig designer to select new transducers optimising the results with a minimum cost.

As usual in this sort of works, it is supposed that the tests are being conducted in almost-adiabatic conditions in a cold test rig. Povedin et al. [6] analyse the influence of different parameters of lubricating oil in the performance of radial turbochargers in almost-adiabatic conditions and it is said that the uncertainty of the measurement can be very problematic at low operating conditions, but no computation of these uncertainties is done. Some authors make their tests in hot conditions. Serrano et al. [7] propose a thermal characterisation methodology successfully applied in a turbocharger, but no uncertainties are quantified. T. Thurnheer et al. [8], present an experimental investigation on different injection strategies in a heavy-duty diesel engine and the uncertainty of different measurements is shown but no propagation is done. Tancrez et al. [9] present a new representation of the turbine performance maps oriented for turbocharger characterisation and it is said when using some representations of turbine maps in numerical simulations the uncertainties of the measurements can propagate very amplified to the final results, so it is very important to quantify them. In the work presented by Günther et al. [10] the deformation and the movement of a high speed rotor is measured and the uncertainties involved are quantified. The authors suggest to calculate the propagation of uncertainties in order to understand how the results can be affected by the propagation effect. Therefore, through this work it is possible to obtain more robust results thanks to the calculus applied to the propagation of uncertainties combined with the sensors selection. In order to optimally select new sensors, a non-linear integer programming problem has to be solved. Several techniques are used in real-world engineering problems involving non-linear programming, as in the work of Zhang et al. [11], and non-linear integer programming, as can be seen in the work of Yokoya [12], Sahoo [13] or Pal [14]. Rose applies an optimisation process to design of experiments to minimise the effect of measurement uncertainties [15]. This work presents one technique suitable for the selection of new experimental equipment in turbocharger gas stands.

This paper is divided in four parts: in the first part the basic equations of uncertainties propagation are presented and the expression for the turbine power uncertainty is developed; in the second part an optimisation methodology to select transducers for a turbocharger test rig is explained; in the third part, the turbine power uncertainty obtained during a typical experimental campaign is shown and compared with the results of Monte Carlo simulations and an optimisation process to select new testing equipment is exposed; last, conclusions and hints to achieve better results are presented.

2. Propagation of uncertainty

Uncertainty in direct measurements is propagated to derived quantities that are of interest such as compressor power or turbine efficiency. To assess the reliability of the measurements of physical quantities, values of their uncertainties should be given in a standardised way. There are different types of methods used to estimate the distribution of the probability density of values of uncertainty for a multivariate system, some of them comprise "Bootstrapping" and "Monte Carlo" methodologies. A good alternative is described in [16] by the Joint Committee for Guides in Metrology and is applied in this work. The objective focuses on finding the standard deviation but