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Statistical model for gas turbine engines exhaust emissions

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A R T I C L E I N F O

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A B S T R A C T

A statistical analysis has been developed from the ICAO databank to predict aero-engines exhaust emissions during a landing and take-off cycle (LTO). The ICAO databank contains updated emission indices for a vast number of turbojet and turbofan engines only, with thrust ratings greater than 26.7 kN. Correlations are developed and proposed for turboprop and turboshaft engines to overcome the difficulty of assessing exhaust emissions from these engines in absence of industry data. LTO emissions are predicted for a turbofan-powered commuter airplane (Embraer E195) using the surrogate model. It is demonstrated that the predictions are closer to the values extracted from the flight data recorder than to the emissions calculated with the ICAO method. Thus, approximate emissions indices applied to actual flight procedures are a better choice than a standard ICAO LTO emission estimate from the databank. The correlations are then applied to the prediction of LTO emissions of a turboprop airplane (Bombardier Q400).

1. Introduction

Fossil fuels are the main source of energy for the commercial aviation, and are likely to remain so for the foreseeable future. Therefore, emissions from combustion of aviation fuel will remain a pressing problem at all levels: from engine design, to meeting ever more stringent targets that are agreed at the international level. To predict such emissions, a number of sophisticated multi-disciplinary software tools have been developed over the years. These tools deal with emissions forecasting on a local and global scale using aggregate data provided by industry, for example Ref. (Kim et al., 2007). Emissions on a global scale have been predicted in a number of projects, and at regular intervals by various organisations, notably NASA (Wilkerson et al., 2010), Eurocontrol, the European Commission, and others (Eyers et al., 2004). A comprehensive review on this matter was published by Masiol and Harrison (2014) in the context of air quality around airports; these authors included an observation that insufficient information was available to evaluate the variability of emissions at reduced engine thrust.

In any case, most of the emission models rely on the ICAO databank (ICAO Engine Emissions Databank, 2017), with the exception of CO_2 emissions, which are directly related to fuel burn (Filippone, 2008). Exhaust emissions are also calculated using additional industry data, empirical and semi-analytic models, independent models of aircraft performance, aerodynamics and propulsion (Nuic, 2004). Particulate matter is excluded from this database. A number of experimental campaigns in recent years highlighted the complexities of the emissions problem with airborne measurements (Timko et al., 2010a,b), and measurements at the airfield (Schürmann et al., 2007). Particulate matter, for which considerable research is also available (for example Zhenhong et al., 2017), is not considered in the present work.

For engineering analysis, the ICAO is the most extensive source of quantitative information, and is continuously updated with contributions from manufacturers. The database now consists of about 500 gas turbine engine versions, including models no longer in service, no longer in production, or superseded. The data are limited to turbofan engines with thrust ratings above 26.7 kN, as there is

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Nomenclature

DoF	Degrees of Freedom
D_p	emission rate
EI	emission index
GPS	Global Positioning System
LTO	Landing- and Take-off
PR	pressure ratio
REI	reference emission index
RMS	Root-mean-square
W_{f6}	fuel flow
$a,b,\ldots,f$	coefficients of interpolating equation
$a_1,\ldots,d_1$	coefficients of interpolating equation
E_I	generic emission index
F_{oo}	rated engine thrust
hm	humidity factor
m	index of a sum; mass
n	number of engines in database
N_1	gas generator speed (also in percent)
r	RMS of the residuals
x_1,x_2	independent variables
WSSR	sum of squared residuals
δ	relative air pressure
θ	relative air temperature
σ	standard deviation

no obligation to report emissions of smaller engines to the regulator (Notably, military engine data are absent from the database, for example several General Electric turbofans and turbojets: F101, F110, F118).

Other ancillary data that may have technical interest are available, for example the engine test dates. These dates can help identify general trends, such as the increase in overall pressure ratios and by-pass ratios over time.

Using the time-in-mode and the fuel flows indicated by the ICAO, we only obtain notional values of the environmental emissions. These are not real-world occurrences, as pointed out by several authors. Actual emissions depend on a large number of factors, which include the actual ground roll procedures, the gross weight, the deterioration of the engines, atmospheric conditions, derating (or part-thrust) and the fuel consumption. Uncertainty effects in emission indices are evaluated by Lee et al. (2007), who point to uncertainty estimates as large as 55% for HC and 26% for CO. Inaccuracies in fuel consumption have been pointed out by a number of authors, notably Senzig et al. (2007) who proposed a method based on data collected from the Flight-Data Recorder (FDR).

Although the emission data are extremely useful, one must be wary of considering these data applicable to all conditions, since the certification is derived from a limited number of tests (typically, 3 new engines), at specified atmospheric conditions and at a fixed altitude. Thus, there are issues concerning engine deterioration effects, variability of performance data across engines of the same family, etc., as also indicated by measurements published by Carslaw et al. (2008) for NO_x. Caution must be exercised when extrapolating these emissions to a global scale and to a long time frame involving future aircraft operations, as it may lead to incorrect conclusions and inappropriate policies.

Deterioration effects can be substantial, as reported in previous research (Lukachko and Waitz, 1997). Lee et al. (2001) also illustrated historical trends in engine emissions. Historical data are available within the ICAO database only as a test date (most of the tests were conducted after 1980). A problem with the test date is that within the database it has no clear correlation with actual technology level. Combustor details are important, but are mostly of commercial nature (“reduced emissions”, “environmental kit”, “phase 3”, etc.), and carry no useful information. Yet, there are a few exceptions. For example, the GE low-emission combustor for the GEnx engines is documented by Foust et al. (2012), and named twin annular premixing swirl (TAPS). This technology shows considerable improvements in emissions at some engine modes over prior architecture. The TALON X technology, documented by Pratt & Whitney McKinney (2007), is used in about a dozen certified engines; it can also be mapped against other combustor technologies, as demonstrated later. Recent research into swirl effects in the combustor (Johnson et al., 2005) shows promising results in reducing emissions, particularly NO_x.

Semi-analytical methods have been proposed on the basis of gas turbine test data (Rizk and Mongia, 1992); it was verified in the course of this work that the correlations proposed do not apply to aero engines. The predictions of these algebraic formulas proposed by Rizk and Mongia are well above the normal values for aero engines. The semi-analytical model has, in principle, the advantage of taking into account other factors, such as the fuel residence time in the combustor, the evaporation time, and the particle size distribution. Unfortunately, these parameters may only be available in aggregate, not specifically for any engine. Therefore, any higher-order model would fail by virtue of uncertainties in the simulation chain. Other engineering methods exist for the prediction of NO_x from gas turbine combustors (Tacina et al., 2008). These, as the previous ones, rely on four key parameters in the combustor: entry pressure and temperature, pressure drop and fuel-to-air ratio – data not readily available from the ICAO database or from the manufacturers. Likewise, it is known that maximum combustion temperatures have slowly increased from about 1800 K to 2000 K in the past 30 years, but data are not published for specific engines.

There are proprietary methods in the industry to estimate exhaust emissions. These methods are not published, not available for research, and are dependent on a larger set of data that is not possible to access for estimates of aviation emissions.

Aside from these caveats, the main motivator of the analysis shown in this paper is the lack of reference data for small engines ($F_{oo} < 26.7$ kN), turboprop and turboshaft engines; this lack of data prevents the simulation of emissions and the comparison with high by-pass ratio engines.

Only a few sparse data exist from turboprop/turboshaft engine manufacturers; data in the literature may include tests of military engines, for example, T700-GE-700 with different fuels (JP4, JP5), which yield different emission rates (Tacina, 1983).

One argument sometimes put forward is that turboprop engines are designed to provide torque rather than thrust. Unless these engines are coupled to a propeller via a gearbox, no useful thrust is generated. However, it is contended here that combustion emissions are ultimately dependent on the combustor design and the aero-thermodynamic conditions inside the combustor,