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"TURBOMATCH-WEBENGINE" – A WEB BASED GAS TURBINE ENIGNE PERFORMANCE ANALYSIS TOOL

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Abstract

This paper discusses the development of a web-based gas turbine performance simulation tool- WebEngine. The main objective of this approach is to enhance the reach of such simulation tools in academia/research and industry. The tool offers a large number of simulation capabilities such as design point and off-design single runs/parametric analysis, engine library, engine model design, virtual engine sensors and power plant operating plan. The *Turbomatch-WebEngine* core is a high quality and robust gas turbine performance simulation code, developed by the Propulsion Engineering Centre at Cranfield University. In addition, the ergonomic graphical user interface offers an easy to use environment even to beginners. Relevant features of the tool are presented towards the end to explain the ease of use of this tool.

Nomenclature

ANN	Artificial Neural Network
BBN	Bayesian Belief Network
DLL	Dynamic Link Library
ESF	Engine Specification file
FL	Fuzzy Logic
GA	Genetic algorithm
GUI	Graphical User Interface
LAN	Local Area Network
LGPA	Linear Gas Path Analysis
NLGPA	Non Linear Gas Path Analysis
TET	Turbine Entry Temperature
VNGV	Variable Nozzle Guide Vanes
VSV	Variable stator Vanes
WWW	World Wide Web

Introduction

Gas turbine performance simulation has always been a field of great interest and has led to extensive research in this field. A variety of engine performance simulation codes covering a wide range of applications, code structures have been developed and made available during the last four decades. The *Turbomatch-WebEngine* is a gas turbine simulation tool developed by the Propulsion Engineering Centre at Cranfield University with an ultimate objective of enhancing its reach to a much wider gas turbine community within academia/research and industry.

The computational power of modern computers has grown in leaps and bounds over the years triggering the development of much complex simulation codes and applications. More advanced cycles and complex engines configuration with realistic attributes were introduced, while the code structure and component interchangeability found greater importance for many research applications. On the other hand, the need for local installation and appropriate configuration became an impediment for its wider applicability e.g. a classic application can be related to situation in academic institutions, where gas turbine performance lectures can be enriched with demonstration of various performance case studies and exercises, but the code must be installed on every computer in the laboratory. In student assignments, there is the need for installation in the students' personal computers. Part-time students, exchange students, short course delegates are disadvantaged by not being able to access the tool when they are away from the University campus. In addition, on many occasions, practicing engineers need to verify certain conditions at their place of work, particularly when time is at premium and will not have the luxury of going to their offices to run a simulation. The web based gas turbine engine simulation aims to fill this gap.

Overview of the tool

The *Turbomatch-WebEngine* is a gas turbine performance simulation tool which is accessible online from any part of the globe merely through a digital device running a web browser and internet connectivity. It incorporates two main technologies. Firstly, a reliable and state-of-the-art performance simulation solver which is the core of the application. Secondly, an ergonomically designed web based GUI and client-server architecture configuration for remote access. *Turbomatch,* which is the core solver for a gas turbine simulation suite, has evolved from extensive research spanning over four decades by the department and has vastly contributed to important gas turbine related research activities and academic publications, providing excellent results in terms of accuracy, stability and consistency. The modular architecture of *Turbomatch* is its strength. The modularity ensures that all future research in component technologies can be incorporated into the tool and preserve the capability of the tool to integrate with other tools, such as optimisers, flow solvers, aircraft simulators etc. The second element is a user-friendly Graphical User Interface (GUI) environment and ability to access from anywhere based on Client-Server architecture is considered to be a novel feature and the strength of this tool At present, the *Turbomatch-WebEngine* is hosted on one of the Cranfield University's servers and can be accessed from anywhere in the world through the World Wide Web. Typically, on registration, the user is allotted a virtual engine and a group of engines as the case may be. These virtual engines are accessible only to the user and can be run at any time. The results are published on the user machine and also stored on the server from which can be downloaded anytime. The flexibility of the tool is such that it can be run from any device capable of browsing the internet including mobile phones, tablets etc. The structure of the tool is shown in figure-1.

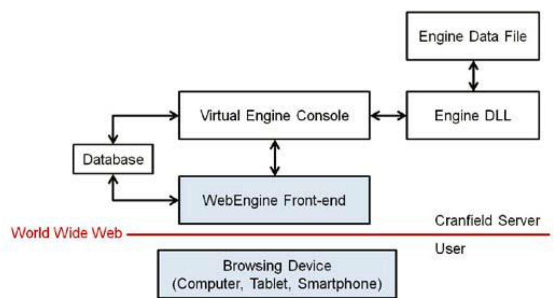

Figure-1: WebEngine Structure

Turbomatch-WebEngine History

It would be most befitting to start by giving an overview of the history of Turbomatch which is a software based Gas Turbine performance simulation tool developed by Propulsion Engineering Centre, Cranfield University. The tool has evolved during the last forty years into an important contributor to research in gas turbine performance simulation. The contributions have come from several members of staff and researchers and has been the mainstay of several important research work over the years.

The first version of *Turbomatch* was developed by MacMillan [1] in the early seventies. The fundamentals were so robust that despite major additions and updates, the basic code structure and philosophy remains the same until now. As was the culture among the scientific community in the earlier days, FORTRAN computer language has been used to develop this application and has continued till date. The tool is capable of performing design point and off-design point simulations of any configuration of civil, military or industrial gas turbine and includes other capabilities, such as degraded component performance, different fuels, water injection/ingestion, variable compressor/turbine geometry etc. have been incorporated.

In *Turbomatch*, technically any of the existing gas turbine engines or conceptual engines can be assembled as a sequence of pre-programmed component modules that represent the gas turbine components like intakes, compressors, combustors, turbines, nozzles, ducts, bleed valves and mixers. Every component unit, referred as Brick, is in reality a mathematical model/routine capable of calculating the thermodynamic process that takes place in that particular engine component. These Bricks have to be provided with certain inputs for the calculations to be performed. Such as, rotational speed, isentropic efficiency, pressure ratio or pressure losses, to name some of them. Since, Bricks are assembled sequentially and suitable interfaces are defined for them to be able to pass on the thermodynamic state of the working fluid from one component to the next. As every Brick imposes a change to the state of the working fluid, the conditions differ in every station along the gas path. Apparently, the exit conditions of the first Brick are the inlet conditions for the second etc. The necessary information that fully describes the gas state is called Station Vector. A Station Vector is provided in every engine station and it consists of eight different variables: fuel-to-air ratio, mass flow, static and total pressure, static and total temperature, velocity and area. In addition to Station Vectors, some Bricks require direct inputs calculated from other Bricks, such as the work of compressors, known as Engine Vector Data. Moreover, some of the Bricks provide results directly to other Bricks, such as thrust or power, variables known as Engine Vector Results. The total flow information to and from a Brick is illustrated in Figure-2.

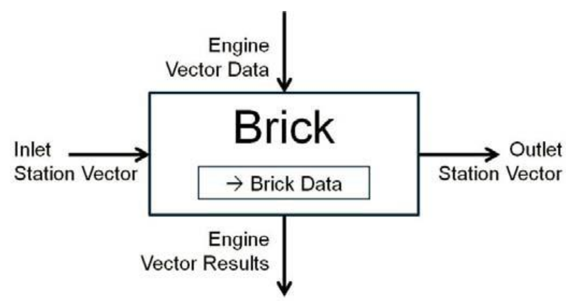

Figure-2: Structure of Brick

A design point is considered as the point where the engine components are designed to operate. This means that the operation is optimum and the engine is sized according to the design point performance [2]. A design point calculation is straight forward. However, in an off-design calculation, the introduction of component maps is essential [3]. As every component will have its own operational constraints, the overall performance of the engine depends of the collective performance of the components. Component maps are derived from experimental work and are indicative of the components' performance characteristics under various operating conditions [4]. Prior to any off-design calculation, a design point calculation is essential in order to size the engine and to scale the maps. The off-design simulation is an iterative process and the code starts with reasonable guesses of a number of parameters and a mass flow, rotational speed, work compatibility is established.

WebEngine Development

As brought out earlier, the motivation to develop such a tool stemmed from the need to create an easy and reliable working gas turbine simulation tool which can be accessed from any part of the world using any kind of device. The department has for very long been trying to address this issue in a way that, while the tools are readily available to students but they are also beneficiaries to any new development or features which are made available from time to time. The WebEngine was conceptualized in early part of 2009 and since then has developed into a versatile application with enhanced features. The *Turbomatch-WebEngine* can practically be run anytime from any part of the world without the complexities of installation/configuration in an easy and effective manner. After more than a year's development and preparations the beta version of the tool went online in January 2011 from a Cranfield University server.

The *Turbomatch-WebEngine* provides immense benefits when compared to conventional locally installed gas turbine simulation tool and a few of them are enumerated below:-

- Remote engine model development and simulation
- No need for any special software and hardware
- Accessible on LAN, WAN and WWW
- Accessible from any part of the world
- Different levels of access, according to user level
- Easy demonstration in classrooms and trials
- Multiple users allowed at any time
- Easy setting-up procedure
- Access to securely remotely stored data
- Access to pre-configured engine models for easy use

While there are several advantages of this method, a few disadvantages identified are, firstly, it is highly dependent on a reliable internet connection. Though the computation is undertaken at the back end server and there is relatively less data exchange with the local device, a slow connection would render the whole process slow. In the event of disruption in internet connectivity the tool would remain unavailable. Data transfer on any network would be exposed to security threats but adequate security measures like firewalls, antivirus programmes can mitigate this.

Turbomatch-WebEngine Features

The *Turbomatch-WebEngine* software tool has undergone several revisions based on beta version trials and regular users' feedback. The development team has constantly strived to enhance the tool's capabilities. Apart from the regular admin and security features, the present version has the following simulation features:

- Run engines and analysis their data from existing library of engines.
- Design new engines using the pre-configured templates or *ab initio* using engine component tools.
- Design point and off-design performance simulation
- Virtual sensor selection and monitoring
- Multiple point parametric analysis and plotting

- Component degradation
- Gas turbine power plant operation simulation

The *Turbomatch-WebEngine* tool has been developed as a user friendly GUI which conceals the underlying complexities of the performance simulation code *Turbomatch* which is highly modular and capable of modeling any type of engine but requires certain level of skill and experience to configure the model for stable operation. In order to use the WebEngine, the user does not need to have any software development skill and just with basic understanding of simulation is sufficient to successfully create and run an engine or make changes to the existing configuration. The application encapsulates several supporting programs and database to support the execution of the WebEngine. The *Turbomatch* has been modified suitably into a DLL which interacts with the database based on the user profile and stores the results in a database post simulation. Adequate error detection and auto correction features have been incorporated to make the experience simple and enriching.

The WebEngine is a very user friendly gas turbine simulation tool with rich features to cater for a wide range of users. The various features are enumerated in the succeeding paragraphs:

(a) Engine Simulation

The *Turbomatch-WebEngine* offers the capability of simulating the performance of numerous pre-configured engines as part of a library. These engines are developed by researchers at Cranfield University and they are thermodynamically similar to a number of popular aero and industrial gas turbine engines, based on information available in public domain. These engines are developed in *Turbomatch* format and uploaded in combination with

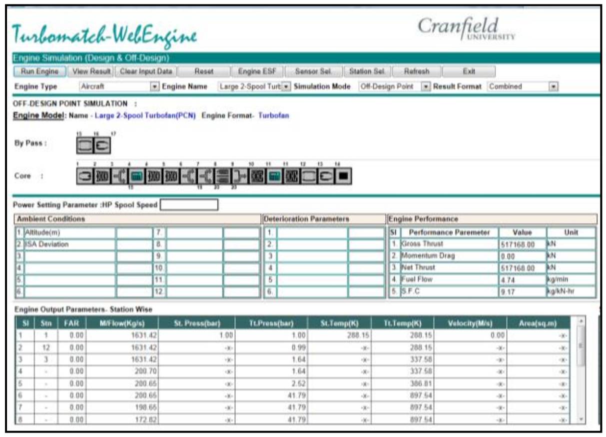

Figure-3: Structure of Brick

relevant Engine Specification file(ESF). A typical engine simulation run for a Large 2-spool engine is shown in figure-3.The GUI shows the component wise (including bleed connections) engine layout for easy understanding. The output in the form of station wise parameters and overall performance parameters are tabulated. In addition to tabular data, the temperature and pressures profiles in the engine at each station can be view graphically as shown in the figure-4 for total temperature at each station:-

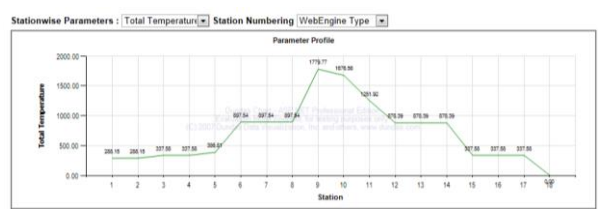

Figure-4: Engine Temperature profile

The ESF files are means of defining the input/output format for the tool. The user can identify the handle to be used e.g. fuel flow, rotation speed, TET etc. In addition, the user could select environmental and power setting parameters, deteriorations data for off-design condition simulation. Station numbering can be designated either in the native WebEngine format or according to SAE nomenclature standard.

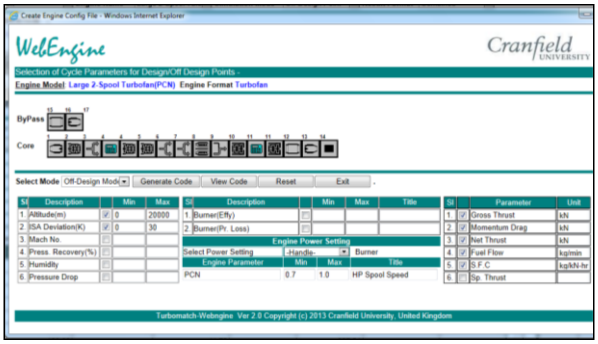

Figure-5: Configuring ESF

The ESF is configured through a user friendly GUI as shown in figure-5.Just by clicking the icons on the engine layout the parameters of that component which can used for off-design condition are shown. Besides, the user can also define the format in which results are required. The detailed results can be downloaded as text files, as excel tables or as graphs. This is a really useful feature as the user, though using an engine available of a remote server but can locally use the results of the simulation.

(b) Engine Parametric Analysis

Apart from the single point simulation, a parametric analysis simulation tool is available for the WebEngine, referred as Series Run. A single point run, as previously described, is sufficient in many cases, but when trends in

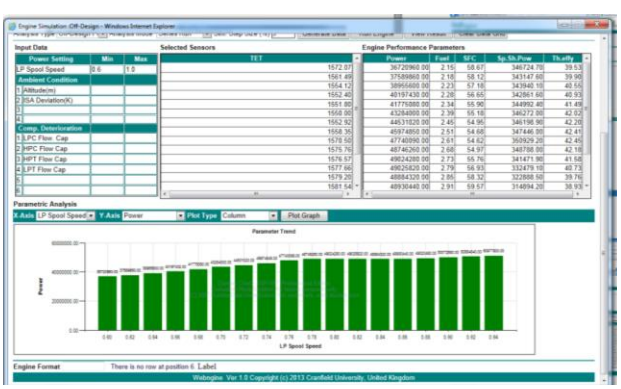

Figure-6: Configuring ESF

performance or design need to be identified, a parametric analysis is necessary. The WebEngine provides parametric analysis for design point as well as off-design condition simulations. The user needs to specify the parameter and provide the tool with a range and a step (in percentage) that is required. The tool internally divides the range into several operating points and simulates at each point. An output from such a simulation is shown in figure-6. Here the Power output is varied against changing LP spool speed. This feature has two options- first one is to simulate a range of parameters and the second one is to change in assorted parameters. It is very useful for comparison.

(c) Sensors Selection

A simulation would require appropriate sensors to measure the parameters. While theoretically any parameter can be captured and displayed but it is important to understand what is actually possible in reality. The tool has a feature in which the user can select the sensor which are required to be monitored and displayed during simulation as shown in figure-7

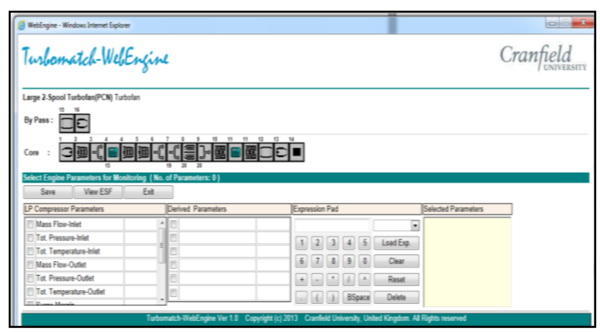

Figure-7: Sensor Selection

In addition, the cycle performance results such as the SFC or the thermal efficiency, thrust or power output etc. though not directly measurable can also be selected as sensor for the purpose of calculation. Moreover, since many of the parameters used in gas turbines are non-dimensional, the user has the freedom of creating any mathematical expression (using virtual keypad) that combines any of the sensors, in order to create customised parameters that fits best for analysis purpose.

(d) New Engine Model Development

While a user has access to all the engine models in the library but it is desirable that option of creating a new engine of any configuration is available. The tool has excellent features to create any engine as shown in figure-8.

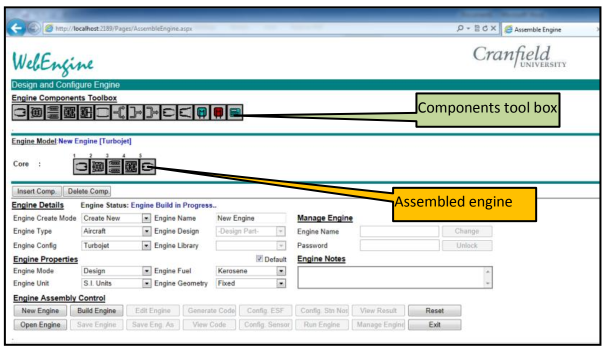

Figure-8: Assembling a new engine

There are two options available to create a new engine. The first one is to use an existing template and fill in the component information according to user requirement. The second option is to create an engine from scratch by assembling the components in a sequence and then providing the component characteristics. Information like type of fuel used, geometry of the engine (i.e. VSV,VNGV), bleed connections/links, bypass ratio etc. The greatest advantage of this method is that the user has the freedom to assemble any engine or undertake novel engine configuration which is an important part of research. This module essentially facilitates the creation of an input file to the *Turbomatch* solver. The *Turbomatch* solver in turn recreates the engine internally to simulate the engine operation. As brought out earlier, this method of creating an engine model is extremely useful as it shields the user from the underlying complexities and presents the whole process in a user friendly manner.

(e) Plant Operation Simulation

It has been shown earlier that *Turbomatch-WebEngine* has a host of features which makes it easy to use. However the most important feature is to be able to simulate actual operating condition and the ability of the tool to seamlessly integrate with other tools. Towards this, several gas turbines model available in the library which are thermodynamically similar to engines used in stationary, marine and aero application can be suitable modified for simulating them in this mode. In case of stationary gas turbines, the user is able to specify the daily and monthly operating schedules for any of single engine or a combination of engines, according to the power demand. Any combination of the schedules is allowed, in order to simulate differences in demand, such as morning/night, weekends, or different times of the year.

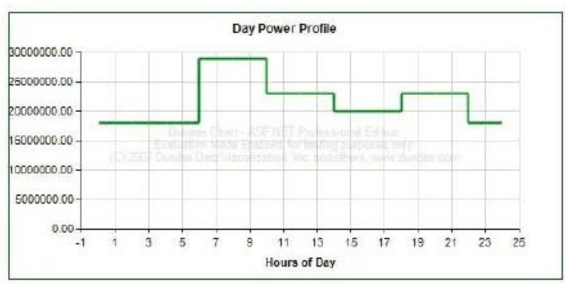

Figure-9: Power profile during a day

A typical power demand is shown in figure-9. Similarly power profiles can be created for different seasons based of engine duty. A month plan is assembled from any combination of day plans and a number of other parameters can be specified. The ambient conditions

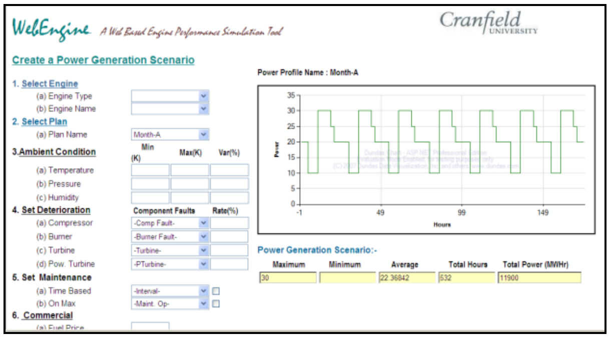

Figure-10: Engine operation profile

and possible variations in the form of standard deviation can be supplied to the model. In addition, deterioration factors can also be introduced in the plan to create realistic scenarios. Maintenance requirements and duration of layoff of the plant can also be input into the model as shown in figure-10. With all the above as inputs, the model is run like it would operate in a real environment. Such virtual scenarios help in understanding various other aspects like the techno-economic benefits, engine life consumptions, maintenance planning, asset management etc.

Conclusion

The *Turbomatch-WebEngine*, a web-based gas turbine performance gas turbine capable of design point and off-design simulations in single or in series of operating points. The platform offers a host of features keeping in mind the requirement of different types of users ranging from students to professionals. The greatest advantage being its accessibility from anywhere and anytime. The added features of running an engine accordingly to a power profile is extremely useful in analysing the engine performance in real time scenarios.

Future Developments

The *Turbomatch-WebEngine* is a project which is constantly undergoing developments based on feedback from users and supporting research, a number of important features are being planned in the future versions. Important aspects like simulation of humidity effects, water/steam injection, alternative fuels etc. Efforts are on to improve the GUI for dynamic plotting capability, enhanced interactive functions etc.

Lastly, a very important future development is the engine diagnostics. Since the diagnostics are an important activity for the propulsion engineering centre with lots of expertise in this field, there is tremendous potential for these diagnostics feature to be introduced into the *Turbomatch-WebEngine*. The long term ambition is to include host of different diagnostics methods, such as LGPA, NLGPA, GA, ANN, FL, and BBN.

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