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A Real-Time Capable Offline Model Twin

Markus Kerellaj[a*], **Markus Wenig**[b] **and Kai Herrmann**[a]

[a] Institute of Thermal and Fluid Engineering (ITFE), University of Applied Sciences and Arts
Northwestern Switzerland (FHNW), Windisch, Switzerland
[b] Winterthur Gas & Diesel Ltd. (WinGD), Winterthur, Switzerland
* markus.kerellaj@fhnw.ch

Abstract

This paper introduces the concept of a Digital Twin (DT) for the purpose of replicating the engine performance and operation of large 2-stroke engines in the maritime industry. Particularly interesting is the fact that the low engine speeds prevailing for this engine type (60-120 rpm) enable the deployment of physical 1D-CFD models at a high modelling fidelity (detailed air path, predictive combustion, etc.). Therefore, an approach for the development of a real-time and transient capable DT model is presented. General feasibility of the approach and real-time capability have been verified (offline). Furthermore, an outlook is given on the application potential of the DT in terms of the engine's design process, the engine operation as well as the virtual simulation and testing possibilities.

Keywords: Control, digital, engine, predictive, twin.

1 INTRODUCTION

Originating from the idea of a virtual representation of a manufacturing factory [1,2] the idea of the DT has quickly emerged to various fields of application like, as, [3] identified mainly three categories – that are design, manufacturing and, becoming increasingly more relevant, prognostics and health management. Of course, the concept of the DT has meanwhile developed further to, for example, model-based system engineering [4] and eventually has not spared the maritime industry [5,6].

Therefore, within this scope, the present paper aims to support the advancement of the DT idea in the maritime industry – by the presentation of a so-called Engine Performance Digital Twin. In fact, only because of the advantageous boundary conditions within the maritime industry (i.e. fast model execution due to low engine speeds + IT infrastructure) it has been possible to deploy a physical engine model instead of surrogate or quasi-static approaches.

2 EXPERIMENTAL SETUP

2.1 Engine

For the research in the context of the present work an engine of WinGD's product portfolio with the type designation "6X72" was used. From the type designation it follows that this is a 6-cylinder engine with a bore diameter of 72 cm.

This 2-stroke in-line engine with a stroke of 3086 mm uses a single turbocharger from the manufacturer ABB in the present configuration. At a nominal speed of 74.7 RPM and 100% load it provides a rated power output of 15080 kW. For illustrative purpose, the following figure (Fig. 1) shows the general experimental setup based on WinGD's test engine "RTX-6" including the engine and the water brake.

Fig. 1 The WinGD RTX-6 test engine

2.2 Instrumentation and data

During the so-called "Shop-test" of the engine, all important engine parameters, (e.g. temperatures, pressures, flow rates) including the turbocharger, have been measured by a variety of measuring points. These measurements are recorded as balance data, these are non-crank angle resolved, time averaged data.

Furthermore, crank angle-resolved measurement data for the cylinder pressure profile and the pressure curve in the inlet and outlet as well as the exhaust valve lift were present. These measuring points on the real engine represent suitable validation criteria for the same positions within the simulation models.

3 MODEL APPROACH

3.1 Fundamentals

The development of the presented engine Digital Twin can be divided into four main categories: the creation of an engine performance simulation model, the implementation of predictive thermodynamic models, the conversion of the model to allow for real-time capability and the coupling with the real engine control system. It should be considered that additional provisions must be made within all of the above mentioned four categories in order to enable the transient capability of the Digital Twin required for later applications.

3.2 Engine performance simulation model

The engine performance simulation model is based on the commercial 0D/1D-CFD simulation software GT-POWER from Gamma Technologies, which represents the current standard in the field of internal combustion engine simulations as well as 1D-CFD simulations in general.

For the present work, it was possible to make use of an already existing engine performance simulation model for the "6X72", which will serve as a base for the further steps in order to create the Digital Twin.

This simulation model includes the entire air path starting with the air filter over the compressor of the turbocharger, the charge air cooler, the scavenge air receiver, the intake ports, the cylinders, the exhaust valves, the exhaust manifold up to the turbocharger exhaust turbines including the wastegate pipe and the continuation up to the outlet. The compressor as well as the turbine of the turbocharger make use of the real turbocharger maps originating from the turbocharger manufacturer.

Based on the technical documentation of a planned or already existing engine, a part or, as in the present case, the entire air path can be modelled by the elements provided by GT-POWER in a suitable way. Essential components of the simulation model are the modelling of the air path itself, including the turbocharger, the intercooler, the fresh air supply and exhaust tract, the combustion chamber and the fuel/air mixture preparation.

Depending on the level of detail required for the desired investigations and the data available for the simulation model, GT-POWER offers different approaches or modelling options for all areas of the model. For illustrative purposes the figure (Fig. 2) below shows the model map of the 6X72 base model with the intake, exhaust and the turbocharger on the left side, the scavenge air receiver in the lower area of the model map, going upwards, followed by the intake port modelling, the cylinders including the injectors and the exhaust tract with the exhaust manifold.

The structure of the simulation model of WinGD was analyzed thoroughly and validated against the measurement data of the real engine, see the previous chapter on EXPERIMENTAL SETUP but also the following chapter VALIDATION AND RESULTS for more details. It showed that this model forms a good basis for the Digital Twin after a few small adjustments.

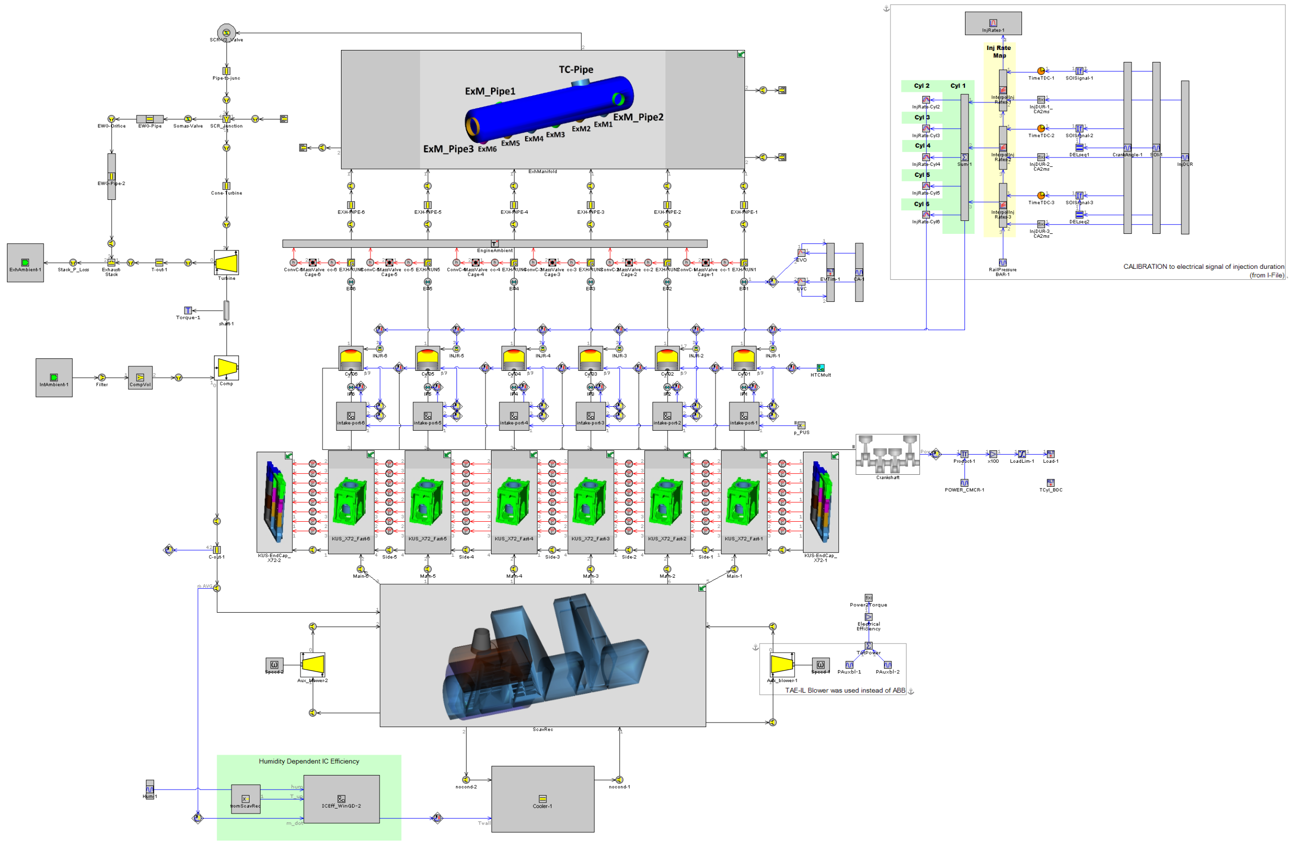

Fig. 2 Model map of the base GT-model

Based on this simulation model, which represents the current state of the art in internal combustion engine simulations, it is now possible to proceed to the actual development steps necessary for the Digital Twin and its desired functional range.

3.3 Predictive combustion model

In order to realize the idea of a transient capable Engine Performance Digital Twin, it is advisable to have a predictive combustion model.

Therefore, the so-called GT-internal "DIPulse" combustion model has been chosen. For direct injected diesel engines, this combustion model allows to predict the combustion rate based on single as well as multi-pulse injection events. The calibration of the DIPulse-model, see [7] for further details, is essential to enable a precise prediction of the combustion rates. The background to this is that at the prevailing, low engine speeds, the process speed is significantly slower than the chemical time scales, which is why there is no premixed component. Accordingly, the parameters for diffusive flame propagation are determined based on measured cylinder pressure curves for a variety of operating points.

It has to be noted that the combustion rate predicted by the model is extremely sensitive to the injection profile as well as to the timing. The injection profiles are defined as maps dependent on the fuel rail pressure and the injection duration. The injection itself then being dependent on the start of injection and the crank angle.

The integration into the existing engine performance model takes place by means of standard GT-modelling elements, which are adapted for the purpose of the injection map definition.

Using a map in map approach for each of the three injectors per cylinder, the fuel mass flow as a function of the time for various injection durations and fuel pressures are defined. This is followed by the individual time delays, depending on the firing order for each injector of each of the six cylinders. These are then added up to form an instantaneous mass flow as currently only one injector with instantaneous injection rate can be specified in a GT-SUITE engine performance model per cylinder. The time-resolved activation of the map-inputs is in turn dependent on the start of injection and, in case of the second and third injector, the time delay between the injectors.

In this standalone model, the main inputs, which are usually provided by the engine control system, are based on the measurement data in look-up tables, depending on other engine parameters. This is in preparation for the coupled model in which the real engine control system communicates directly with the engine performance simulation model.

Ultimately, the output is a time-resolved or crank angle-resolved specification of the instantaneous fuel mass flow rate for one single injector per cylinder. The following figure (Fig. 3) shows a close-up of the mentioned structure for the map-based injection system. The corresponding block can be found in the upper right corner of the model map in the previous figure (Fig. 2).

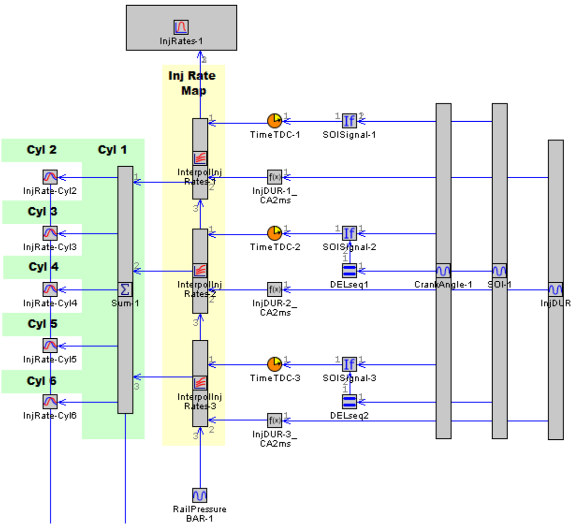

Fig. 3 Model map section of the injection system

3.4 Real-time simulation

As a first step to build a real-time capable simulation model, a simplification of the flow paths in being undertaken. This reduces the number of sub volumes, while at the same time it allows the solver-time steps to be increased. Due to these adjustments, a significant computational speed up can be achieved, which ultimately enables the simulation model to run faster than real-time.

In the development of a real-time-capable simulation model, the relation between accuracy and run-time should always be taken into account. Depending on the application, due to the simplifications in the flow path, accuracy losses will occur. Therefore, a meaningful conversion process of the simulation model to real-time capability had to be defined.

Compared to other approaches to realizing the real-time capability of a GT-POWER simulation model, the chosen approach offers several advantages. In particular, a major advantage compared to other approaches is the fact that the engine topology can be maintained, equal to the real engine. In addition, and this is at least of the same importance, if not to classify higher, is the fact that an FRM represents a dynamic model and not a static map as compared to other approaches. This in combination with the use of the previously mentioned "predictive combustion model" ultimately makes it possible to realize a transient and real-time capable engine performance simulation model.

As usual, there are also disadvantages. Due to the adjustments mentioned above, accuracy losses are to be expected in the course of FRM creation. However, these can be compensated by a suitable recalibration strategy.

In general, it also has to be noted that the modelling approach of the physical model-based DT only works so well due to the low engine speeds. Typically, the speed of a large, 2-stroke engine is in the range of 60-120 RPM.

Depending on the architecture and the modelling approach of the base model which is to be speed up to real time capability different conversion steps arise.

First of all, the main influencing factors on the simulation time are to be determined, whereby it should be noted that these vary, for example, depending on the operating point of the simulation model to be investigated. It is advisable to repeat these examinations after each adaptation or calculation time optimization since changes may occur. In the present case, it has been shown that both the exhaust manifold and the scavenge air receiver, both originally modeled by semi-automated conversion processes based on their CAD models, have a significant impact on computation time. These were therefore completely rebuilt directly in GT-POWER using the GT-POWER flow path elements.

In order to give a brief insight in the actual modelling within the simulation model the figure (Fig. 4) below shows the original 3D-CAD based scavenge air receiver and its surroundings, followed by the figure (Fig. 5) that shows the structure inside the original 3D-CAD scavenge air receiver.

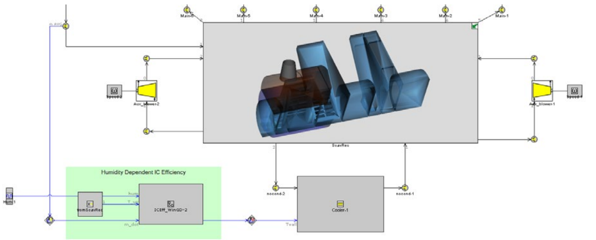

Fig. 4 Model map of the initial scavenge air receiver

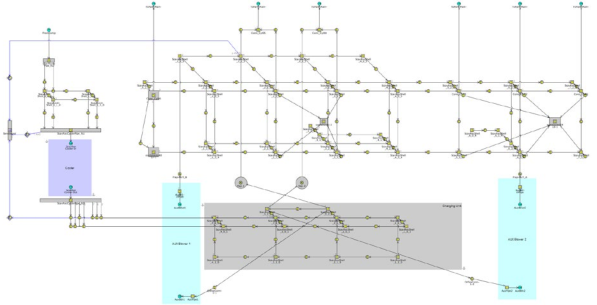

Fig. 5 Flow path in original scavenge air receiver

Again, similar to the procedure for the "exhaust manifold" based on the pictures of the shop-test, the flow path was newly built in GT-POWER, taking into account the connections of the two electric blowers and the intercooler. This while maintaining the total volume, which could be determined from CAD data.

The newly and directly in GT-POWER built scavenge air receiver can be seen in the figure (Fig. 6) below, while taking into account all the existing connections and their functionality as well as maintaining the total volume.

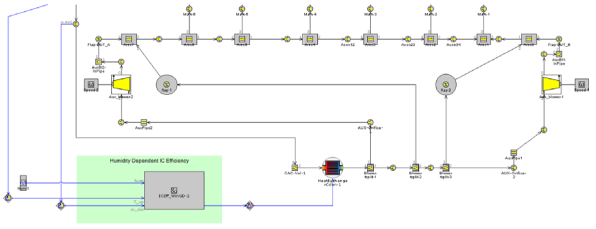

Fig. 6 Flow path in the new scavenge air receiver

Furthermore, a different modelling of the charge air cooler also significantly increased its computing performance.

In addition to these modifications, the discretization length for the flow path elements was increased, but also the output settings were optimized, by reducing the output requests. Following the conversion of the model to real-time capability, a detailed, step-by-step recalibration based on the measurement data had been performed.

Again, having the later use of the model in the focus, it becomes apparent, that a simulation of the model in the so-called load-mode instead of the previously and usually for GT-POWER simulations used speed mode, is to be considered more meaningful. Using the so-called "speed-mode" in GT means the engine speed is being defined by the user, instead using the so-called "load-mode" means the user defines the load torque required from the engine simulation model. Therefore, as in the real case with the water brake, a load torque is applied to the engine

Correspondingly, the simulation model had to be converted to load-mode in an appropriate manner. Based on the chosen setup for the torque element it is possible to simulate both fixed pitch propeller as well as continuous pitch propeller operating points.

3.5 Integrated simulation

Subsequently, the model coupling of the real engine control system, which is based on SIMULINK, with the GT-POWER engine performance model has been conducted.

As already mentioned in the introduction and explained in detail in the following chapters APPLICATION and CONCLUSIONS, the realization of the Digital Twin creates a wide variety of possible applications in the design process as well as in the area of engine operation and virtual testing and simulation.

The "Model Coupling" generally refers to the coupling of two simulation models, which are mostly based on different software programs. The coupling allows different models or tools to be simulated together. In comparison, in one of the two programs, the entire system to be simulated can be constructed only partially or at great expense.

Depending on the application and in this case on the desired functional range of the Digital Twin, different model coupling strategies for the different areas of research are needed, their respective feasibility had to be clarified. Basically, there are three variants for the model coupling between the ECS and the engine performance model, the following list gives an overview:

- GT as Master: SIMULINK integrated in GT
- SIMULINK as Master: GT integrated in SL
- Co-simulation: GT-POWER with SIMULINK

It should be noted that for the "Model Coupling"-variants with "GT as Master" only a GT-POWER license is required. In contrast, the "SIMULINK as Master"-variant requires both a MATLAB/SIMULINK- and a GT-POWER-license. In the Co-simulation setup both simulation programs calculate simultaneously, therefore requiring a GT-POWER and a MATLAB/SIMULINK license yet no conversion and implementation of the one simulation model into the other model is necessary. The Co-simulation variant has been investigated and proven to be applicable as well, however due to its computational expense and the planned applications it does not play an important role.

The following figure (Fig. 7) gives an abstracted view on the model coupling options chosen for the Digital Twin:

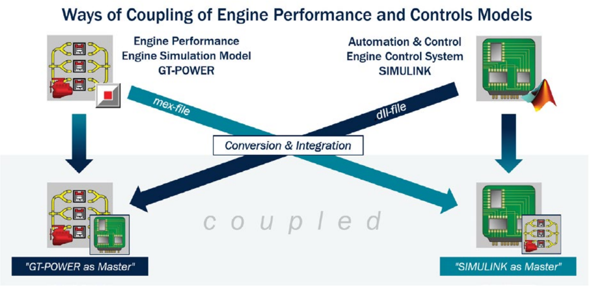

Fig. 7 Digital Twin model coupling overview

As already mentioned, by means of the "Model Coupling" complex systems can be simulated holistically, which opens up completely new possibilities for both areas, for the development of the "Engine Control System" and for the development of the engine itself.

In order to create a Digital Twin it is of vital importance to understand the behavior of the engine control system and even more so, the parameters that are being exchanged between the engine or in this case of the Digital Twin the engine performance simulation model and the engine control system.

The "Engine Control System", in short ECS of WinGD is a partially SIMULINK based engine control.

In the course of the investigations for the feasibility of a Digital Twin, the ECS interfaces were reduced to the eight inputs and the nine outputs that connect the ECS with the engine. The values for the inputs to the ECS, in turn, come from the GT-POWER engine model, thus a loop between engine control and the engine model is formed by means of the "Model Coupling".

Due to the high complexity in the field of "Model Coupling", a strategic approach to find an applicable strategy is inevitable. Therefore, in a first step, instead of the complex engine control system, a simple SIMULINK model has been created. This self-created, so-called "simpleSIMULINK" model could thus be used to determine the basic feasibility of "Model Coupling" and the necessary settings and operations.

This "simpleSIMULINK" outputs the values for the "start of injection" and the "injection duration" which have previously been defined directly in the engine performance model. By doing so it is possible to separately investigate the behavior of the coupling without adding additional levels of complexity at this first step. The values for "start of injection" as well as "Injection duration" are dependent on the "Engine-speed" which is the input value originating from the engine performance model. Depending on the speed and therefore also the load point, since the engine will be used in conjunction with a fixed pitch propeller, at which the engine operates, lookup tables provide the correct injection values for the above-mentioned parameters.

The following figure (Fig. 8) shows the "simpleSIMULINK"- model with the two lookup tables in which the corresponding injection values are stored as a function of engine speed.

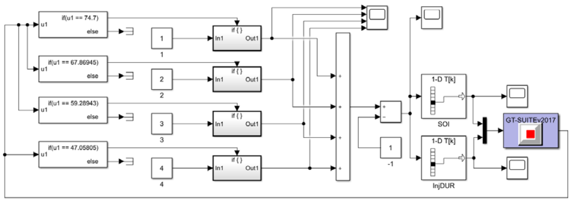

Fig. 8 "simpleSIMULINK"-model testing

On the right side of the upper figure (Fig. 9) the special GT-SUITE element for coupling with SIMULINK is depicted.

In addition to the creation of the illustrated SIMULINK model, adjustments to the GT-POWER model must also be made for the coupling and therefore for the basic clarification of the feasibility.

For this purpose, see the following figure (Fig. 9), which shows a section of the model map, visible in the right edge is the so-called "SIMULINKHarness" which allows the coupling between SIMULINK and GT-POWER and replaces the tables formerly defined directly in GT-POWER with the inputs and outputs from the "simpleSIMULINK" model.

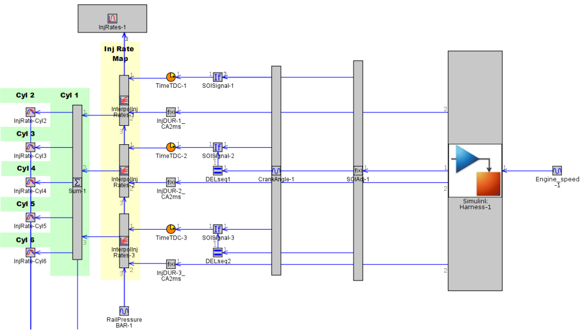

Fig. 9 Model map of the SIMULINK harness

The steps involved in the coupling after the investigations for the "simpleSIMULINK" and with the above mentioned preparations, both in the SIMULINK as well as in the GT-POWER simulation models in the "GT as Master" version, are as follows: Building the simple model in SIMULINK; testing the model in a standalone configuration within SIMULINK; implementing the special GT-SUITE element for model coupling; defining the solver and the code generation settings, converting the "simpleSIMULINK" model to a .dll-file for the use in the version "GT as Master"; implementing the .dll-file in the prepared GT-POWER engine performance simulation model in the version "GT as Master", containing the "SIMULINKHarness" element; running the .dll-file in the GT-POWER model with "GT as Master".

Once the coupled model in the version "GT as Master" has been created it is then relatively simple to create the coupled model in the "SIMULINK as Master" version. In order to do so, firstly, after some mandatory changes to the "SIMULINKHarness" a mex-file of the existing "GT as Master" GT-POWER model has to be created. Then this model has to be implemented into the existing “GT as Master” SIMULINK model, here again making changes to the settings of the GT-SUITE specific SIMULINK element.

With the selected step-by-step approach, not only the feasibility could be determined but also an efficient strategy for the coupling process was found. This process makes the traceability of each step possible without any problems and greatly simplifies any troubleshooting.

After the general procedure could be defined with a simplified model for the coupling, for the real engine control system coupling in a first step, the input and output parameters have to be defined. These are the parameters which are to be exchanged between the SIMULINK and the GT-POWER simulation model. The definition of parameters to be exchanged is strongly dependent on the structure of the engine control model in SIMULINK as well as the GT-POWER simulation model, but also on the intended application.

In the present case, the following parameters of Table 1 as well as Table 2 have been defined as exchange parameters.

The same procedure as described above for coupling with the "simpleSIMULINK" model created for testing could now be used to create the integrated simulation model with the real engine control system.

For illustrative purposes the below figure (Fig. 10) shows the model map of the Digital Twin, an engine performance model which is both real time as well as transient capable with an integrated, real engine control system and a predictive combustion model.

Table 1. Input parameters (from GT to SIMULINK)

No.	*Parameter*
1	Engine speed
2	Engine speed relative to max. engine speed
3	Fuel rail pressure
4	Bottom dead center
5	Scavenge air pressure
6	Crankshaft average brake power
7	Top dead center
8	Speed set point

Table 2. Output parameters (from SIMULINK to GT)

No.	*Parameter*
1	Injection start angle 1
2	Injection duration 1
3	Injection start angle 2
4	Injection duration 2
5	Injection start angle 3
6	Injection duration 3
7	Waste gate angle
8	Exhaust valve closing angle
9	Exhaust valve opening angle

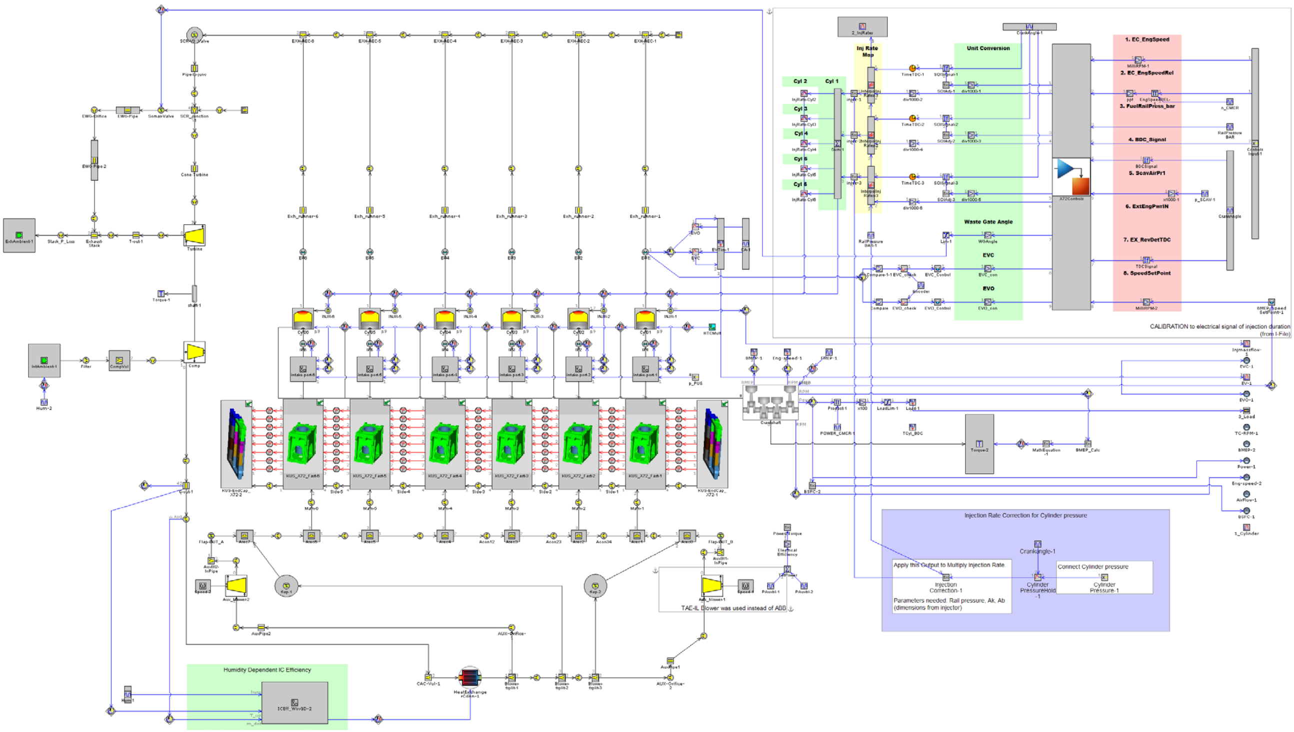

Fig. 10 GT-POWER model map of the Digital Twin

4 CHALLENGES

Looking at the previous chapter of the “MODEL APPROACH” there are a few challenges, the most outstanding ones of its generation will be mentioned in the following section.

First of all, a physical engine performance simulation model has to be built, calibrated as well as validated. Even though this is seen as state of the art nowadays, implementing phenomenological sub-models, which allow for predictive modelling are still rarely used.

The challenge especially increases when a combination of these sub-models, as in the case of the Digital Twin, with a simplified gas dynamics model is to be realized in order to achieve a real time and transient capable simulation model. In this field the degree of simplification to the flow path which does have an important influence on the computational speed of the simulation, has to be balanced against the desired simulation accuracy.

In addition, the complexity of the simulation model increases significantly with the coupling of engine and control system. This already begins with the actual definition of the parameters to be exchanged. This is usually followed by extensive conversions of all model parameters to realize the transient capability of the model and to turn the simulation in load mode.

Not to be forgotten is the increased debugging effort due to the combined usage of two different simulation models and simulation tools, in this case being GT-POWER and SIMULINK. However, a strategic approach for the model coupling based on extensive standalone tests of the single models with test setups for the expected in- and outputs followed by a defined coupling process itself can greatly reduce the likelihood for errors.

5 VALIDATION AND RESULTS

5.1 Validation quantities

Using the available measurement data of the real engine, the 6X72 from WinGD, a validation concept, which is applicable for all stages of expansion within the development of the Digital Twin, has been defined.

For the air path, all pressures (p) and temperatures (T) starting at the ambient state (pa/Ta) to the position before the compressor (p1/T1), after the compressor (p2/T2), after the intercooler, or in the scavenge air receiver (p3/T3) up to the conditions in front of the turbine (p4/T4) and after the turbine, or in the exhaust system (p5/T5) were detected in a time-averaged manner.

Furthermore, the fresh air mass flow at the inlet (m°i) and the exhaust gas mass flow at the outlet (m°e), positioned after the merging of the exhaust waste gate line and the turbocharger exhaust side, are measured. The speed of the turbocharger (TCR), which is a very important and relevant measure since it has a very large impact on the entire engine operation, is also being recorded. Both the power (kW) and the engine speed (RPM) are measured at the water brake. The cylinder pressure (pcyl) is being measured with a crank angle resolution of 0.1°CA steps, whereby the firing pressure (fp) also originates from this measurement.

Based on further measurement data recorded on the engine, depicting or explaining the used measuring points would exceed the scope of this paper in any case, the efficiency of the turbine (Et), the efficiency of the compressor (Ec), the Brake Specific Air Consumption (BSAC), the Brake Specific Fuel Consumption (BSFC) and, ultimately, the Percentage Load (%) have been calculated and can therefore be used as validation criteria, since these important validation criteria, in the case of GT-POWER, can directly be exported from the simulation model results.

The following figure (Fig. 11) shows the GT-POWER model map extended to a measuring point scheme, presenting an overview on all available validation criteria, in the development stage of the previously mentioned "Fast Running Model". In contrast to the original model, see (Fig. 2), this can be seen, although most of the adjustments are not directly visible on the model map, especially due to the new scavenge air receiver and the new exhaust manifold in the lower and upper, middle area of the picture.

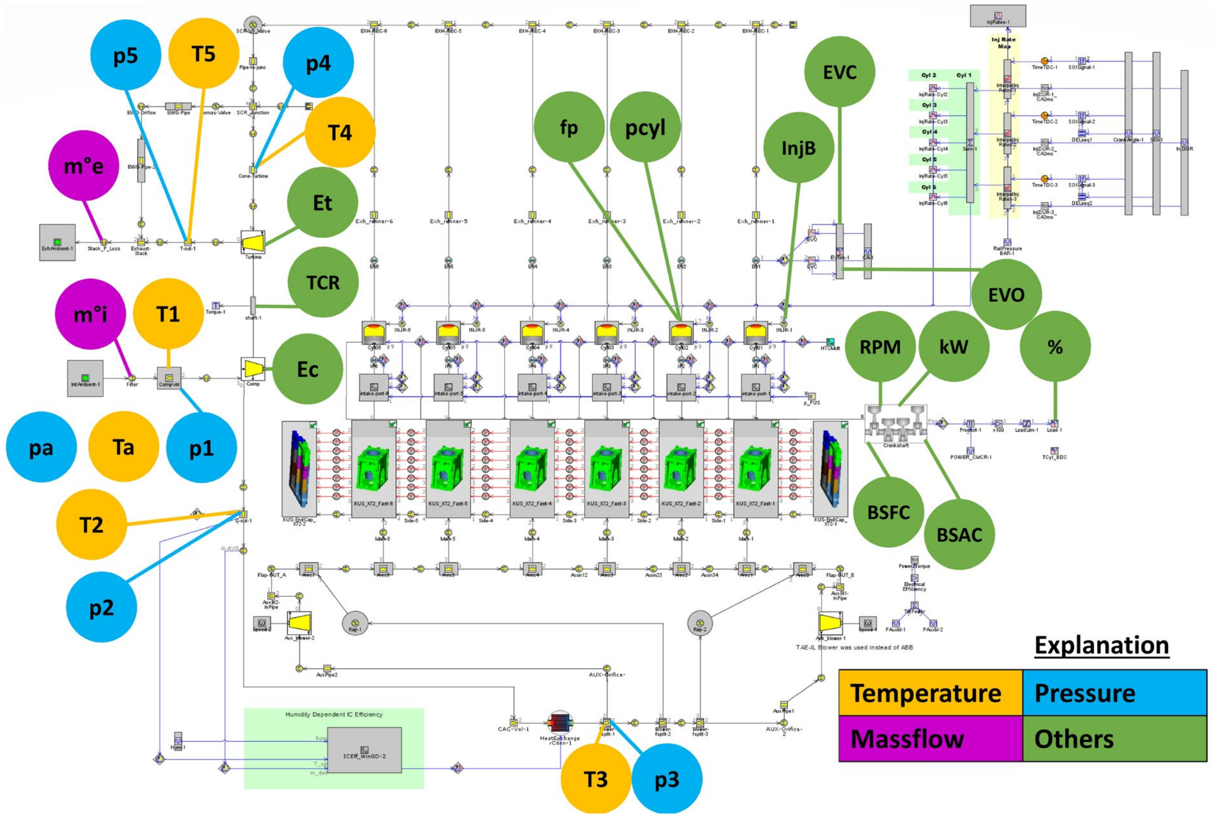

Fig. 11 Measuring point scheme of the 6X72

5.2 Validation

Based on the correct parameterization of the engine control system and the resulting correctness for all output parameters, a clear refinement of the simulation results can be achieved. This is based on the fact that the coupling with the engine control system enables a much more detailed and realistic definition of the injection parameters within the simulation model.

In this regard, a significant refinement could be achieved for the maximum (percentage) deviations for all measuring points, see the measuring point scheme (Fig. 11) for details. This despite the fact that the model was converted to a so-called “Fast Running Model” (FRM). Among the calculated operating points (25/50/75/100% load) the largest percentage deviation across all pressure measuring points (within the engine air path) was at 4.5%. Correspondingly, the maximum temperature deviation was at 10 K and the fresh air mass flow could be matched with a maximum tolerance of 5.8%.

The following figure (Fig. 12) allows for a comparison of the simulation model accuracies of the initial, “detailed simulation model” without coupling and the final, coupled “GT as Master” simulation model for the most relevant operating points at 75% and 100% load, against the measurement data.

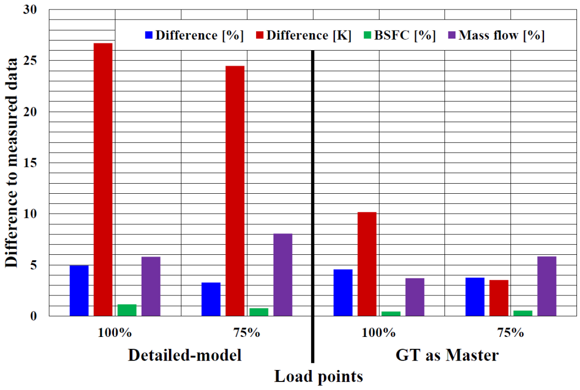

Fig. 12 Model comparison and validation

Additionally, the following figure (Fig. 13) as an example shows a comparison between the measured pressure curve and the pressure curve simulated with the Digital Twin at 100% load.

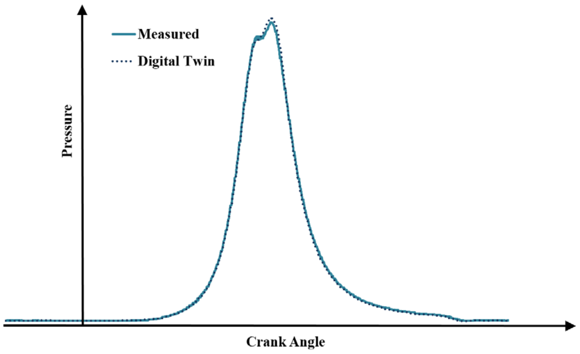

Fig. 13 In-cylinder pressure curve at 100% load

5.3 Results

Firstly, an analysis of the current development process in the area of engine control system development but also in the area of engine performance model development could be carried out. This has been followed by a detailed analysis of the functionalities of the related simulation models.

Based on this detailed analysis, in a further step the basic procedure for the coupling could be defined and the feasibility confirmed.

In the area of the subsequent coupling of the engine performance model with the real, Simulink-based engine control, this simulation model, or to be precise its conversion and integration, which are necessary for the coupling, turned out to be a special challenge.

The processes in creating the coupled, real-time capable simulation models connecting the actual GT-POWER engine performance models with the real SIMULINK engine control system could be defined and tested in detail, ultimately proving the feasibility of the coupling. The real-time capability of the coupled models could also be confirmed by reaching a real-time factor of 0.6 x RT (i.e. the model was roughly 1.6 times faster than real engine operation) while maintaining a high accuracy of the simulation results as shown previously.

6 APPLICATION

Although the effort of creating such a detailed Engine Performance DT seems high at first glance, it can well be justified.

Based on the idea that an engine Digital Twin may form the central element of a streamlined engine model development from the early concept phase to the final online application. During this continuous development process, the DT is constantly refined and extended, and, furthermore, a variety of synergies and thus process optimizations can be created.

As already mentioned, the Digital Twin offers great potential in the optimization and simplification of the development steps from the early concept phase through the proof of concept up to the final development steps of the engine including its periphery.

For example, the Digital Twin approach will be implemented in WinGD’s future design process, using both “Software in the Loop” as well as “Hardware in the Loop” methods for the engine control system development.

Additionally, driven by the recent rise of the artificial intelligence technologies (AI), the Digital Twin can enter an even broader field of application. In this field of development, for example, the Digital Twin can supply the large amounts of data necessary for the training of the neural networks as well as for the reinforcement learning. Already today, WinGD’s Engine Performance DT is utilized to train neural networks for internal development purposes.

In the future, the Digital Twin will not only find application in the area of engine development but also in the area of engine operation. With the Digital Twin and the use of artificial intelligence (AI) technologies it will be possible to realize an engine monitoring system with predictive maintenance functionality.

Last but not least, a newly created "Virtual Engine Test Stand" (RTX-V) provides new offline training capabilities (without the risk of damaging the engine). For example, changes in the periphery of the engine but also in the engine control system can be investigated and their transient behavior and their influence on the entire engine can be analyzed. With the virtual test bench, real testing campaigns can also be simulated in advance to generate relevant data, which can support both the preparation and the performance of the real tests and thus optimize the whole process.

Equal to the real engine test stand, the speed set point of the engine as well as the load torque applied by the water brake can be actuated by the user. In addition to the controllers, monitors similar to the real test stand, which allows the analysis or control of predefined parameters during the simulation, have been defined.

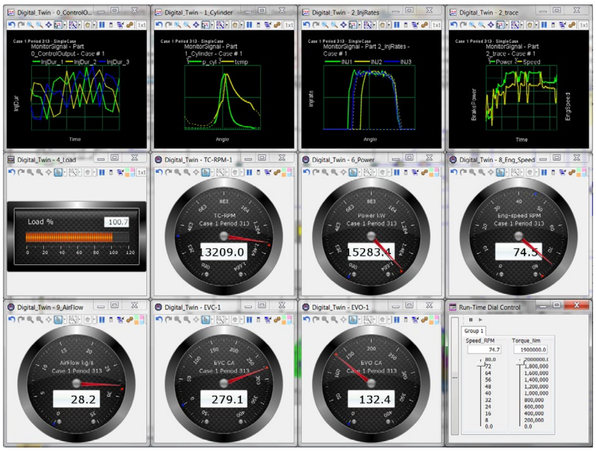

Fig. 14 Control panel of the virtual engine test stand

For illustrative purposes the above figure (Fig. 14) shows a simplified variant of the control panel with the actuators for the speed set point and the water brake torque in the lower right corner.

7 CONCLUSIONS

The focus of this study lay on the development of a physical offline model twin and the corresponding feasibility of online operation. In this regard, the concept of applying a physical model approach to the development of an offline DT (i.e. predictive GT-POWER model coupled to a SIMULINK controls model) for the eventual purpose of diagnostic, prognostic, and health management could be proven since RT capability and model accuracy are given. Furthermore, synergies with other areas of application result in further benefits. For example, the presented Engine Performance DT could be further repurposed for, both "Hardware in the Loop" (HiL) and "Software in the Loop" (SiL) applications as well as transient engine performance simulation, the buildup of a virtual test bed and in doing so, for example, utilized for virtual trainings. Ideally, the development of a DT is not isolated from the development of the already existing engine and controls models in the company. Instead, the DT development should be integrated in order to achieve a stream-lined workflow from the early concept to the final implementation phase.

Additionally, the proposed DT approach involves a physical engine model including predictive sub-models which allows for high model predictivity (even outside of calibrated model ranges). This, indeed, is only possible due to the fact that two-stroke engines in the maritime sector usually operate a low engine speeds (approx. 60-120 RPM) and therefore provide an excellent opportunity for the application of physical model-based Digital Twin.

Nevertheless, further improvements particularly in terms of model fidelity and process automation are necessary. In the end, this evolutionary process shall allow for an automatic generation of the DT for a given engine type, including the calibration, and coupling of the necessary controls model. In terms of deeper integration, GT-POWER offers great potential to include even more aspects of the whole engine and the surroundings in the Digital Twin. So far, the Digital Twin is described as an Engine Performance Digital Twin, focusing on the thermodynamic/fluid mechanic aspects, with the combustion process being the center point of interest and therefore, since it plays a vital aspect in this area, the integrated engine control system.

However, future planning may also involve extension of the Digital Twin approach for directly incorporating even more aspects of the engine development process (e.g. detailed component temperatures). As examples at this point the development of a CAD-based thermal finite element cylinder model, as well as the development of a piston ring heat transfer model that takes into account both mechanical, tribological and thermal aspects should be mentioned. The real-time capability required for the Digital Twin and its areas of application currently requires simplifications of the simulation model at the expense of their accuracy.

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