

A TRANSIENT MODEL OF A TURBOFAN ENGINE IN SIMULINK

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Abstract

Modern turbofan engine performance is heavily influenced by the thermal efficiency of the high pressure compressor and high pressure turbine. A transient model of the high pressure system of an IAE V2500 is therefore developed. It consists of the high pressure compressor, combustion chamber and high pressure turbine. In this simulation setup, each component is modelled by its respective component map. To achieve the most accurate read-out of the component maps, different approaches for their implementation into the simulation have been examined. To further increase the models accuracy, the gas properties dependency on temperature and chemical composition of the fluid is taken into account. The properties of the gas are calculated for each station along the gas path. Downstream of the combustion chamber, the composition of the fluid varies dependent on the fuel to air ratio. Due to the fact, the chemical reaction in the combustion chamber is included in the simulation setup. The combination of advanced map read-out methods and variable gas properties leads to a model in Simulink which shows the transient behaviour of the high pressure system and converges to a reliable steady state.

1. INTRODUCTION

Due to the influence of the high pressure system's thermal efficiency on the overall performance of turbofan engines, the simulation of the gas generator including deterioration effects should be used to develop safer and more effective engines. To avoid compressor surge conditions, the operating line, which is the line in a compressor component map the compressors of turbofan engine work on during steady states, needs to have a sufficient surge margin. Surge margins are necessary because the compressors of a turbofan engine are forced to leave their operating lines towards the surge line during acceleration. In addition, deterioration effects lower the surge margin during engine operation. This means a portion caused by deterioration effects needs to be added to the surge margin which is necessary for acceleration. The resulting large stock surge margins needed in today's turbofan engines lead to lower compressor efficiencies being compensated by an increased fuel mass flow. Adapting the engine operation to the current condition promises benefits in fuel consumption.

The efficient and accurate read-out of performance characteristics like pressure ratios and efficiencies derived from component maps is primarily focused in this paper. To allow an efficient change of component maps, the preparation and building of data structures required for the simulation is fully automated by scripts. These scripts ensure the timesaving usage of different component maps to simulate different engines or deteriorated components. Since the simulation is based on the characteristics of the high pressure compressor (HPC) and high pressure turbine (HPT), the accuracy of the derived data is of vital importance to the reliability of the results. Therefore several methods for obtaining the required component characteristics are developed, having individual advantages and disadvantages which are discussed and combined, resulting in a dependable simulation of the gas generator.

Moreover, the change of the gas properties through the engine cycle has a great influence on the dynamic behaviour of jet engines. The properties of air vary primarily in relation to the chemical composition and temperature. Varying properties are accordingly implemented in the model of the gas generator. Because of the chemical composition is constant up to the combustion chamber, it is assumed that the characteristic properties of gas passing the HPC are only a function of temperature. For all components located downstream from the combustion chamber, chemical reactions taking place in the combustion chamber are additionally taken into account.

2. SIMULINK MODEL

2.1. Definition of reference planes

Following the definition proposed by KURZKE [1], the turbofans' reference planes are shown in FIGURE 1. Defining the stations like this reduces the complexity of the comparison between an existing reference model of an IAE V2500 in GasTurb and the results of model build in Simulink.

Since the bypass stream, located between stations 13 to 18, and the low pressure section of the core consisting of low pressure compressor (LPC), low pressure turbine (LPT) and nozzle, are not modelled in the simulation, the stations 25 to 44 are explained in detail. Beginning at station 25, the air is compressed in the HPC to the high pressure level at station 3, followed by the combustion chamber from station 31 to 4 where the fuel mass flow is injected, mixed with the pressurized air and ignited. Therefore, the combustion gas enters the HPT at station 41 at high a temperature and pressure. The enthalpy of the gas is converted to shaft power by the HPT, which drives the HPC. The gas exits the HPT at station 44 at a lower pressure and temperature and streams through the LPT and nozzle.

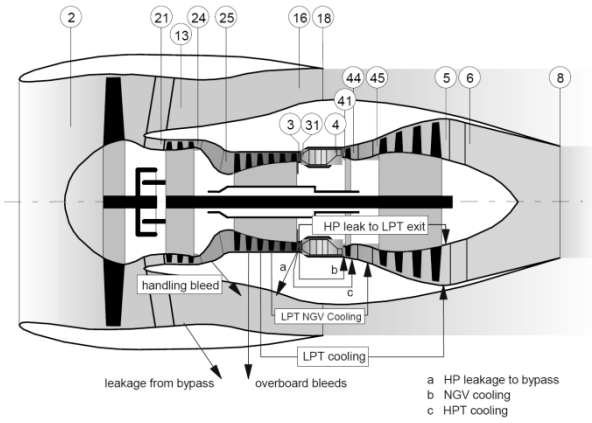


FIGURE 1. Reference Planes, KURZKE [1]

2.2. Model setup

As presented in FIGURE 3 the Simulink model consists of two main modules, which contain the calculation methods for the HPC and HPT. Because of the missing low pressure section and nozzle, quantities defined by these components are constants. In addition the combustion chamber is simulated by a constant temperature. The constant values are taken from the reference simulation performed in GasTurb to ensure comparability between the results of the Simulink model and the GasTurb reference simulation. Each main module consists of a set of submodules performing different computations. The HPC module as well as the HPT module contain at least two submodules. Component map modules determine the characteristics of the respective component and pass these quantities over to the thermodynamics module. As an example of such a system the HPC module is given in FIGURE 2.

Due to the modular set-up, the model can be extended and enhanced by additional modules or by exchange of present ones.

2.3. Variable gas properties

As already mentioned, the properties of the gas heavily affect the results of the high pressure system's simulation. As RIVKIN [2] observed, the isobaric heat capacity c_p of air depends on the temperature. This means the pressure's influence is negligible below 5 MPa. Under this condition the isobaric heat capacity is expressible as a polynomial. According to RIVKIN [2], the polynomial is a regression based on spectroscopic measurements and can be formulated as

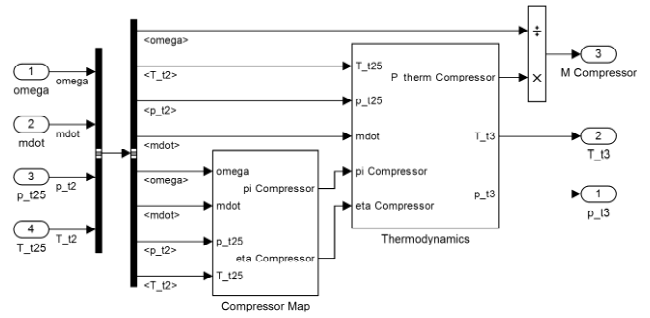


FIGURE 2. High pressure compressor module

$$(1) \quad c_{p,Air} = \frac{1}{\mu_{Air}} \sum_{n=-1}^7 a_n^c \left(\frac{T}{1000} \right)^n \left[\frac{kJ}{kg \cdot K} \right].$$

In EQ. 1 μ_{Air} is the molecular weight of air in kg/kmol and T the average temperature in Kelvin. The coefficients a_n can be found in RIVKIN [2] and these are valid for a temperature range up to 1500°C. Using the average temperature between the compressor inlet and outlet, the isobaric heat capacity of the air passing the HPC can be calculated.

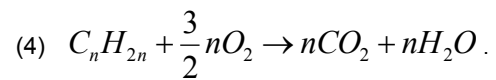
The computation of the isobaric heat capacity downstream of the combustion chamber is more complicated. Due to the variable fuel to air ratio

$$(2) \quad f = \frac{\dot{m}_{Fuel}}{\dot{m}_{Air}},$$

the chemical composition varies. It is therefore necessary to discuss the chemical reaction taking place in the combustion chamber. As POWELL [3] has argued, the structural formula of kerosene can be defined as

$$(3) \quad C_n H_{2n}.$$

In combination with air, many potential reaction products exist. According to POWELL [4], the influence of carbon dioxide and water outweigh the influence of other reaction products, because their proportion is greater by several powers of ten. This means the chemical reaction of kerosene and oxygen is limited to



Dividing EQ. 4 by n and substituting the reactants by their respective molar weights, which can be found in

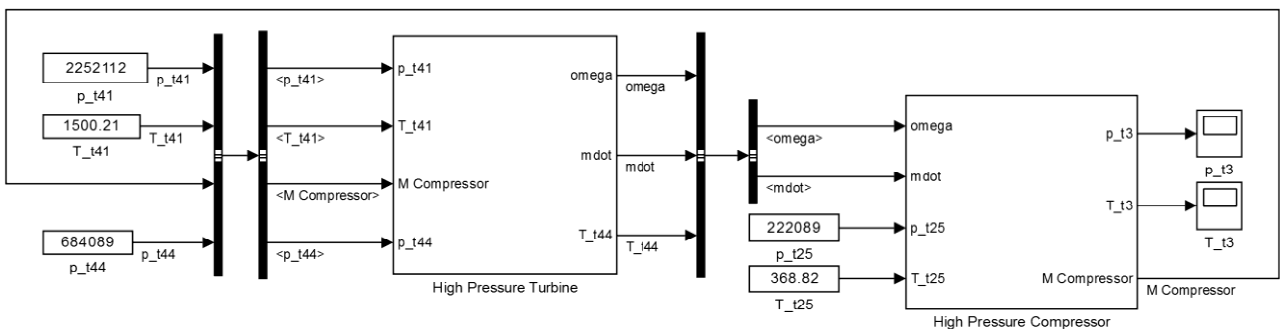


FIGURE 3. Overview of the Simulink model

BRÄUNLING [5], leads to the equation

$$(5) \quad \mu_{CH_2} + \frac{3}{2} \mu_{O_2} \rightarrow \mu_{CO_2} + \mu_{H_2O}.$$

From this, the ratios oxygen to air, carbon dioxide to air as well as water to air can be expressed as a function of the fuel to air ratio as follows:

$$(6) \quad f_{O_2} = f \cdot \frac{\mu_{O_2}}{\mu_{CH_2}} = 3.4219 \cdot f$$

$$(7) \quad f_{CO_2} = f \cdot \frac{\mu_{CO_2}}{\mu_{CH_2}} = 3.13755 \cdot f$$

$$(8) \quad f_{H_2O} = f \cdot \frac{\mu_{H_2O}}{\mu_{CH_2}} = 1.28434 \cdot f$$

Finally, the combination of the ratios given in EQ. 6 to EQ. 8 with the mass fractions of dry air leads to the proportions after the combustion in relation to the fuel to air ratio.

$$(9) \quad f'_{N_2} = 0.75515$$

$$(10) \quad f'_{O_2} = 0.23142 - 3.4219 \cdot f$$

$$(11) \quad f'_{Ar} = 0.01288$$

$$(12) \quad f'_{CO_2} = 0.00055 + 3.13755 \cdot f$$

$$(13) \quad f'_{H_2O} = 1.28434 \cdot f$$

These equations are used to compute the isobaric heat capacity of the combustion gas using the mathematical statement presented by BRÄUNLING [5]

$$(14) \quad c'_p = \frac{\sum c_{p,i} f'_i}{1 + f} \left[\frac{J}{kg \cdot K} \right].$$

By analogy with RIVKIN [2], BRÄUNLING [5] suggests a polynomial regression for the individual heat capacities $c_{p,i}$. Deviating from RIVKIN, BRÄUNLING chooses forth degree polynomials, which have valid temperature range from 1000K to 2500K. This set of equation enables the simulation to provide heat capacities depending on temperature and the chemical composition of the fluid. Since the heat capacities are used to compute the acceleration of the high pressure system by calculating the difference between the power used by the HPC and released by the HPT, they have a huge influence on the results.

Furthermore the isobaric heat capacities are used to calculate the isentropic exponents κ_i at each station of the high pressure system. The rearrangement of basic thermodynamic relations leads to the expression

$$(15) \quad \kappa_i = \frac{c_{p,i}}{c_{p,i} - R_{s,i}}.$$

This means κ_i is a function of the isobaric heat capacities and the specific gas constant $R_{s,i}$ of the fluid. Specific gas constants for different gases can be found in RIVKIN [2], including the one for dry air, which is used for the high pressure compressor. Variable chemical gas compositions occurring downstream of the combustion chamber require the computation of the specific gas constant in each time step. In general, specific gas constants can be calculated dividing the universal gas constant $R_m=8.314471J/molK$ by the molar weight of the gas. Because of that, the molar weight of the combustion gas needs to be known. Molar weights of gaseous mixtures, assuming the ideal gas law is followed, can be calculated using Amagat's law presented in BRÄUNLING [5]. It states that the molar weight of gaseous mixtures is composed of the total mass of all components and the number moles present in the mixture. Using already calculated values, the rule can be expressed as

$$(16) \quad \mu_{Gas} = \frac{1 + f}{\sum \frac{f'_i}{\mu_i}}.$$

A combination of the equations presented in this section is used to compute the properties of the fluid passing the HPC and HPT in each time step.

2.4. Component maps

The component maps describe the characteristics of the HPC and HPT in relation to their respective independent variables. To eliminate ambient influences, dependent variables are plotted against corrected quantities. In case of the HPC, the independent or input quantities are the corrected mass flow \dot{m}_{corr} and the corrected HPC spool speed n_{corr} . Without taking Reynolds number effects into account, the corrected mass flow and spool speed are, according to BRÄUNLING [5], defined as

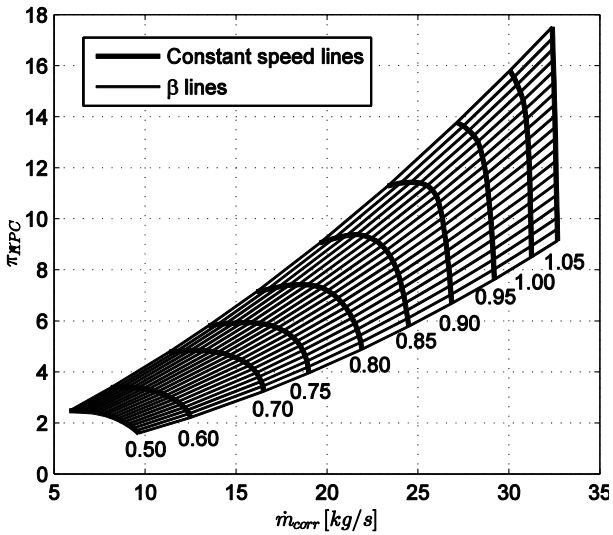
$$(17) \quad \dot{m}_{corr} = \dot{m} \sqrt{\frac{T_t}{T_{ref}}} \frac{p_t}{p_{ref}} \text{ and}$$

$$(18) \quad n_{corr} = \frac{n}{\sqrt{\frac{T_t}{T_{ref}}}},$$

where T_t and p_t represent the total temperature and total pressure at station 25 whereas T_{ref} and p_{ref} represent the standard day conditions stated in the international standard atmosphere (ISA). Instead of the absolute HPC spool speed, the maps being used for the transient simulation of turbofan engines are measured in relation to the relative corrected HPC spool speed $n_{rel,corr}$, which is defined as

$$(19) \quad n_{rel,corr} = \frac{n_{corr}}{n_{corr,Design}}.$$

The dependent or output variables of compressor maps are the total pressure ratio π_{HPC} and the HPC efficiency η_{HPC} . These values are used to calculate the combustion chamber's inlet temperature and pressure, hence they influence the shaft power used by the HPC.

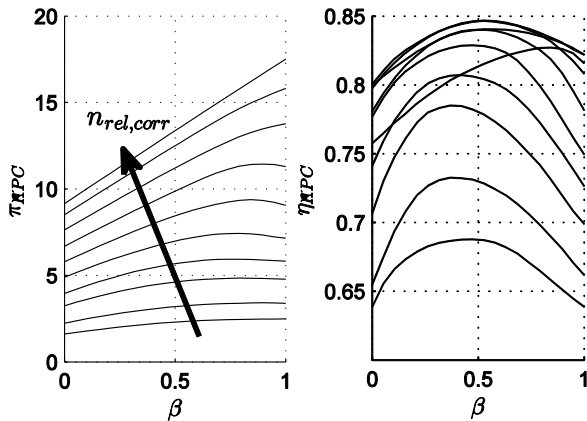

FIGURE 4. High pressure compressor map

Quantities stored in the component maps are measured at constant spool speeds. Each line of constant speed extends from the low pressure ratio choke line to the high pressure ratio surge line. The constant speed lines are shown in FIGURE 4. Because the dependent variables are known at discrete points, it is necessary to implement a two-dimensional interpolation at each time step during the simulation.

Different independent variables are used to calculate the output variables of the HPT map. Although the relative corrected HPT spool speed is also used as one of the input quantities, the second one is the pressure ratio π_{HPT} which is defined as

$$(20) \pi_{HPT} = \frac{p_{t,41}}{p_{t,44}}$$

Assuming the mass flow handled by the gas generator is determined by the HPT because the speed of sound is reached in the narrowest cross section of inlet guide vanes or first row rotor rotors, the geometry determines the mass flow being handled by the HPC and HPT. Therefore the first output variable is the corrected HPT mass flow, which is converted to the corrected HPC mass flow and used as an input variable for the HPC map. The efficiency of the HPT is the second information extracted from the HPT map and is used to compute the total


FIGURE 6. Set of high pressure compressor maps

temperature downstream of the HPT as well as the shaft power transferred to the high pressure compressor.

2.5. Map scaling

For the transient simulation of an IAE V2500 turbofan engine corresponding component maps need to be available. As the original maps are unavailable, scaled maps are used in their place. The scaling process is based on a design point calculation of the whole engine. After the design point calculation, efficiencies η_{Design} , pressure ratios π_{Design} and mass flows \dot{m}_{Design} are compared to the values of a reference point on the existing map, whereby the reference point should be chosen to be nearby the design point of the reference engine. Reynolds effects are factored in using the coefficients $f_{\eta,RNI}$ and $f_{\dot{m},RNI}$ as proposed by KURZKE [6]. This leads to the scaling factors for the efficiency, mass flow and pressure ratio

$$(21) f_{\eta} = \frac{\eta_{Design}}{\eta_{Reference} \cdot f_{\eta,RNI}},$$

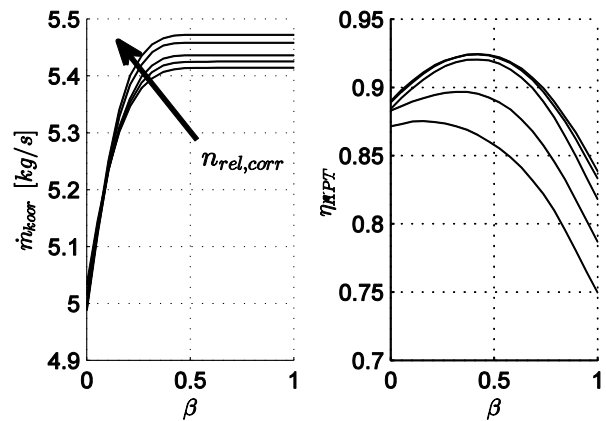
$$(22) f_{\dot{m}} = \frac{\dot{m}_{corr,Design}}{\dot{m}_{corr,Reference} \cdot f_{\dot{m},RNI}},$$

$$(23) f_{\pi} = \frac{\pi_{Design} - 1}{\pi_{Reference} - 1}.$$

After multiplying all values of the reference map with their corresponding scaling factors, the scaled map of the IAE V2500, shown in FIGURE 4, can be used for the simulation. For reliable simulation results, reference maps related to the target engine maps need to be used in order to achieve a realistic dynamic behaviour.

2.6. Beta lines

Steep gradients at low pressure ratios of the constant speed lines, which are shown in FIGURE 4, require the introduction of β lines. Each line of constant speed is intersected by a given number of β lines at equally spaced points on the speed lines. Per definition the coordinate β has the numerical value zero at the choke line and one at the surge line in case of a compressor map. Deviating from that, the coordinate β in a turbine map is defined as zero at the lowest pressure ratio and 1 at the highest pressure ratio. This makes it possible to interpret the


FIGURE 5. Set of high pressure turbine maps

dependent variables π_{HPC} and η_{HPC} or \dot{m}_{HPT} and η_{HPT} as a function of the relative corrected spool speed $n_{rel,corr}$ and β and leads to a set of simpler maps, two for each component map. For a given spool speed and β , it is easy to calculate the corresponding dependent variables due to moderate gradients shown in FIGURE 5 and FIGURE 6. The dependent variables are plotted against the coordinate β for each line of constant speed.

Since the data representations in FIGURE 5 and FIGURE 6 of the characteristic component maps are well suited for the automated processing during the simulation, it is clear that an interpolation between the speed lines is necessary to manage any spool speed. Another problem, discussed later, arises from the exact calculation of the coordinate β in compressor maps. For that reason the calculation methods defining β_{HPT} are presented here and the different methods for the calculation of β_{HPC} are discussed later. β_{HPT} is linearly dependent on the pressure ratio over the turbine and can therefore be expressed as

$$(24) \beta_{HPT} = \frac{\pi_{HPT} - \pi_{HPT,min}}{\pi_{HPT,max} - \pi_{HPT,min}},$$

where minimum and maximum pressure ratios are interpolated values dependent on the relative spool speed at each time step during the simulation.

2.7. Spool speed calculation

The calculation of the spool speed couples the thermodynamic and mechanical quantities. The interesting mechanical quantity for the simulation is the spool speed, because it is an independent variable of the component maps. To couple the various quantities, the derivative of the angular momentum with respect to time is used. Neglecting single forces, the derivative can be expressed as the sum of all external momenta. The summation is equal to the product of the moment of inertia J and the angular acceleration $\dot{\omega}$.

$$(25) \frac{dL}{dt} = \sum_{i=1}^n M_i = J \cdot \dot{\omega}$$

This equation needs to be completed by an expression which defines the sum of the external momenta M_i . Such a relation can be found by introducing the definition of the mechanical power P_{mech} .

$$(26) P_{mech} = M_i \cdot \omega$$

Rearrangement of EQ. (26) leads to the desired expression to define the momenta. The mechanical power consumed by the HPC is equivalent to the thermodynamic power transferred into the fluid

$$(27) P_{therm,HPC} = \dot{m}_{HPC} \cdot c_{p,HPC} \cdot \Delta T_{HPC}$$

Analog considerations are valid for the high pressure turbine, because it converts the enthalpy of the combustion gas into mechanical power, which drives the HPC. The last missing mathematical statement is the temperature difference of the HPC and HPT. Those can be calculated by rearranging the definition of the respective isentropic efficiencies

$$(28) T_{t,3} = T_{t,25} \left(1 + \frac{\pi_{HPC}^{\frac{\kappa-1}{\kappa}} - 1}{\eta_{HPC}} \right) \text{ and}$$

$$(29) T_{t,44} = T_{t,41} \left(1 - \eta_{HPT} \left(1 - \pi_{HPT}^{\frac{\kappa-1}{\kappa}} \right) \right).$$

Due to the fact that the HPC and HPT are mounted on the same shaft, they rotate at the same angular speed ω . Similar rotation speeds cause the sum of momenta to be reduced to

$$(30) \sum M_i = \frac{P_{therm,HPT} - P_{therm,HPC}}{\omega}.$$

An integration of EQ. (23) finally leads to the expression combining all the thermodynamic quantities, which are derived from the component maps and basic definitions, and the mechanical spool speed.

$$(31) \omega = \int \frac{P_{therm,HPT} - P_{therm,HPC}}{\omega \cdot J} dt + \omega_0$$

3. DEVELOPMENT OF BETA CALCULATION METHODS

3.1. Linear interpolation of characteristics

In analogy with the problems resulting from steep gradients discussed earlier, the function $\beta_{HPC}(\dot{m})$ has a similar behaviour like the function $\pi_{HPC}(\dot{m})$. This can be seen in FIGURE 7, where β_{HPC} is plotted against the corrected mass flow for different lines of constant speed.

The easiest method to compute an approximation of the desired value is a set of piecewise linear functions for each line of constant speed. Linear pieces can be calculated based on measurements recorded during test bed runs. The challenge of this method is finding the linear piece belonging to the given mass flow on a linearly interpolated constant speed line. This is done by accomplishing the interpolation of the constant speed line based on the current angular speed at first. Afterwards, a MATLAB script looks for the two mass flows below and above the actual mass flow and calculates β_{HPC} , a linear connectedness assumed, based on this data. β_{HPC} and the relative corrected spool speed are then used to calculate the dependent HPC variables, which are based on the representation of FIGURE 6. Again, a linear interpolation between the different constant speed lines is performed, followed by an interpolation between the interpolated characteristics. The simplicity of this method is outweighed

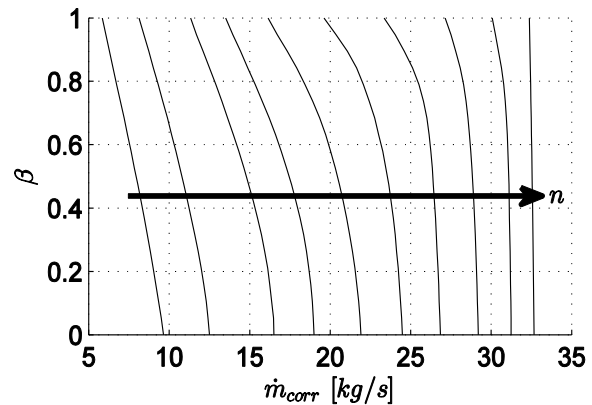


FIGURE 7. β_{HPC} as a function of \dot{m}_{HPC}

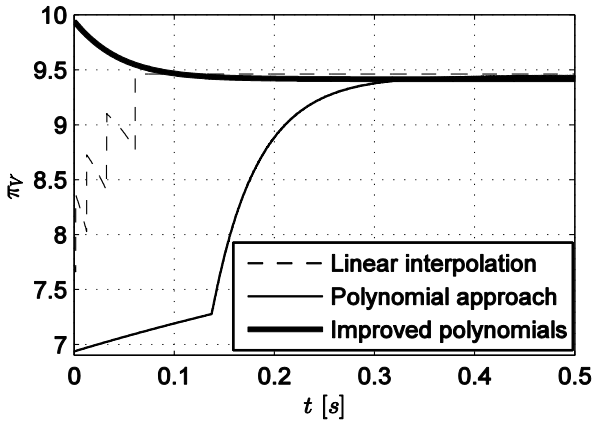


FIGURE 8. Dynamic properties of HPC pressure ratio

by unphysical discontinuities, which can be seen in the resulting dynamic behaviour plotted in FIGURE 8. Discontinuous results are ascribed to the intersections of linear pieces, because at each intersection the slope changes abruptly. Changes of slope find expression in all output variables. For this reason, the linear interpolation method needs to be converted to a continuous one.

3.2. Characteristics based on regressions

Avoiding piecewise linear approximations directly leads to regressions. In this paper, regressions used for data representation are polynomials because of their straightforward mathematical definition and properties. All data stored in the component maps are represented as polynomials with respect to their corresponding independent variable. This is automatically done by a script programmed in MATLAB. For best results the script computes polynomials of degree one to nine for each data set in a least square sense. Afterwards the resulting deviations from the given data basis are compared and the polynomial featuring the lowest sum of squared residuals is chosen. In this manner the output variables π_{HPC} , η_{HPC} , \dot{m}_{HPT} and η_{HPT} are converted to continuous functions depending on their corresponding β . Due to the fact that the dependent variables are known on constant speed lines, a linear interpolation is implemented in the Simulink model.

In case of the coordinate β_{HPT} the computation remains unchanged because of its linear dependency on the pressure ratio π_{HPT} . By contrast, the coordinate β_{HPC} is non-linear in relation to the corrected HPC mass flow and shows nearly vertical sections as presented in FIGURE 7. Hence the coordinate β_{HPC} is converted to a polynomial using the method described above. After this conversion, all quantities are expressed in a continuous manner leading to improved simulation results.

In FIGURE 8 the results of this approach are shown. Obviously the abrupt changes no longer occur, but another problem arises from this solution. Due to the steep gradients, polynomials are inaccurate in those segments. Further investigations on the deviations showed that β_{HPC} differs widely, up to 29%, from the original values. As a result, the computed β_{HPC} is negative in the beginning of the simulation. The definition of β determines values from zero to one. Negative values or values greater than one would imply an extrapolation beyond the operating limits of the high pressure compressor. To avoid extrapolations, limiters, which restrict the computed values to the defined

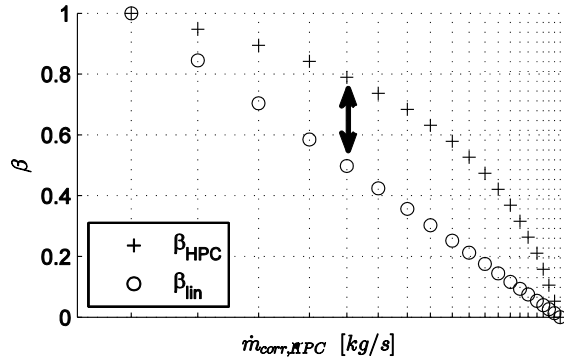


FIGURE 9. Split β lines

range, are implemented into the Simulink model. The restriction causes a hypothetical operation along the choke line of the HPC until the incorrect coordinate β_{HPC} becomes greater than zero.

3.3. Improvement of regressions

The conversion of the set of piecewise linear functions to polynomials solves the problem of unphysical simulation results. Near the choke line of the high pressure compressor the inaccuracy of the regression needs to be eliminated. This is accomplished by splitting the polynomials into a linear portion and a non-linear portion. Linear portions of the polynomials are defined as functions of the corrected mass flow. By definition β_{HPC} is equal to zero at the choke line and one at the surge line. As can be seen in FIGURE 7, at a constant speed, the minimum mass flow is located at the surge line, whereas the maximum mass flow is reached at the choke line. Combining this observation with the definition of β_{HPC} , unique linear portions for each constant speed line can be calculated. As an example, this is presented in FIGURE 9, which shows β_{HPC} of one constant speed line. The difference between the linear portion β_{lin} and the true value of β_{HPC} can then be expressed in terms of the linear portion leading to the expression

$$(32) \beta_{HPC} = \beta_{lin}(\dot{m}_{corr,HPC}) + \beta_{Diff}(\beta_{lin}).$$

The non-linear term β_{Diff} is then calculated using the same script and method as used before for the computation of the regressions. As a result of the split, the trend of the non-linear portion is well suited for possible trends of polynomial regressions, which can be seen in FIGURE 10. Redefining β_{HPC} like this has two important advantages. The most important one is the fact that β_{HPC} cannot leave its defined range and the polynomial

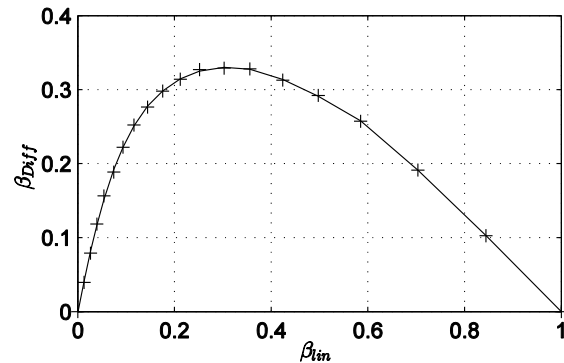


FIGURE 10. β_{Diff} as a function of β_{lin}

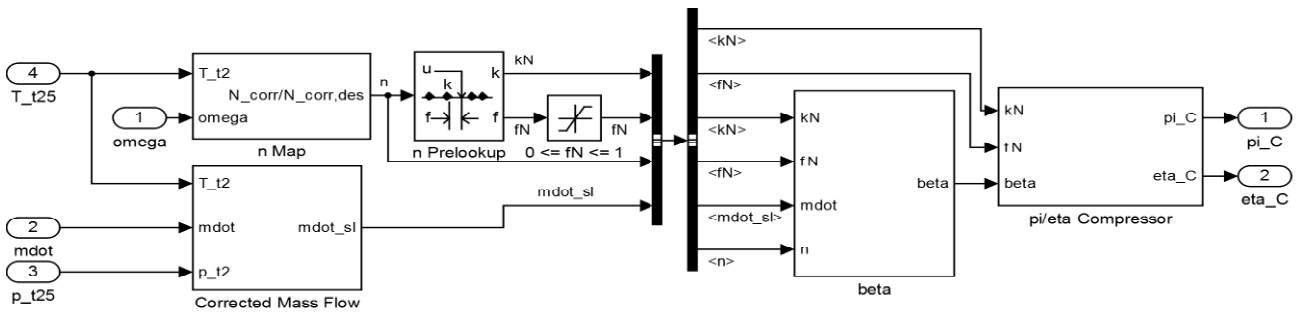


FIGURE 11. Subsystem Compressor Map

regressions are more exact than the ones used before. Additional advantages are the less steep gradients of the linear portion.

The results of this improvement are shown in FIGURE 8. It can be seen that all unphysical behaviour is eliminated from the results. Due to the exact computation of β_{HPC} , the dynamic characteristics are correctly calculated between surge and choke lines and no hypothetical operations occur along the limits.

The implementation of the component map calculation is presented in FIGURE 11 by the example of the HPC. At first the corrected mass flow is calculated in relation to the total pressure and temperature at the HPC's inlet. The relative corrected spool speed is then computed based on the total temperature and passed over to a prelookup block which finds the corresponding constant speed lines. Resulting from the prelookup block, the interpolation coefficients are combined with the corrected mass flow and passed to the subsystem beta. This subsystem, presented in FIGURE 12, computes the coordinate β_{HPC} , which is used to calculate the pressure ratio and efficiency of the HPC.

The calculation of β_{HPC} follows the improved regression method. In a first step, the subsystem beta checks if the corrected mass flow is processable at the given speed. In case either the choke line or the surge line is reached, the warning block prompts a message and the limiter block restricts the mass flow to the corresponding limit. Below the mass flow check-up, the coefficient blocks interpolate the coefficients of the polynomials which describe the relation between the mass flow and β_{HPC} . The interpolated coefficients are subsequently passed over to the polynomial evaluation blocks and β_{HPC} is returned to the subsystem Compressor Map in FIGURE 11.

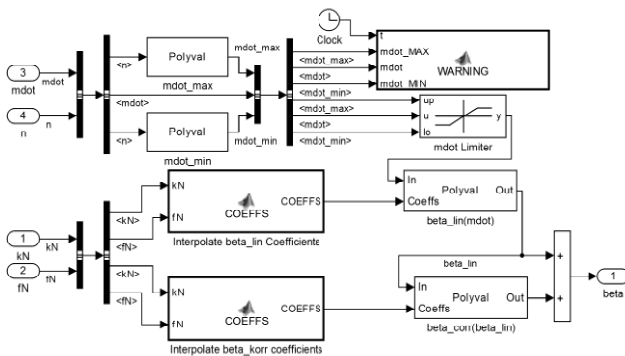


FIGURE 12. Implementation of β_{HPC}

3.4. Implementation of variable gas properties

Up to this point, the simulation uses the ideal gas law. For further improvement of the model's accuracy, variable gas properties are implemented in the model at this point. Like mentioned before, the gas properties of the HPC depend only on the temperature. The function, which describes the isobaric heat capacity, is a polynomial regression. Due to the fact the heat capacity belongs to the thermodynamic quantities, it can be found in one of the subsystems of the thermodynamics subsystem shown in FIGURE 2.

The gas properties of the fluid which flows through the turbine are a variable mixture of combustion products. Reaction products need to be included consequently in the model. The implementation of the isobaric heat capacity is given in FIGURE 13. Due to not-yet-modelled combustion chamber, a stoichiometric combustion is assumed. The simulation of the gas properties, which depend on the chemical components, is therefore constant. Nevertheless, these values are calculated to ensure the expandability of the model.

To ensure that the model is precise as possible, the mean temperature between inlet and outlet of the HPT is calculated, followed by computation of the individual component heat capacities. After that, the heat capacities are summed in relation to the chemical reaction in the combustion chamber and passed over to the subsystem computing the thermodynamic power, which is converted to shaft power by the HPT.

For the prediction of the temperature downstream of the HPT, the isentropic exponent κ_{HPT} is necessary. In case of air following the ideal gas law the isentropic exponent is constant. Because of the changing mixture of combustion products and the dependency on the temperature of the isobaric heat capacity, it is predicted using the subsystem of FIGURE 15. The main part of this subsystem is the estimation of the molar weight of the combustion gas by using Amagat's law, which is required for the computation

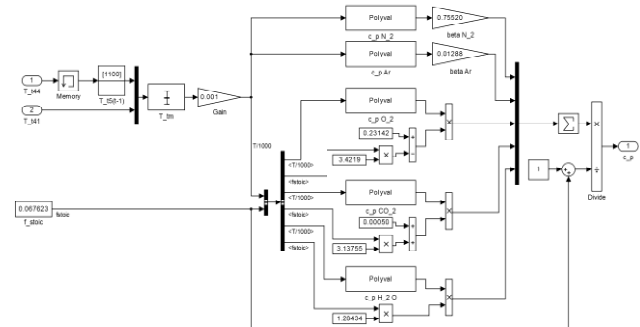


FIGURE 13. Implementation of the isobaric heat capacity

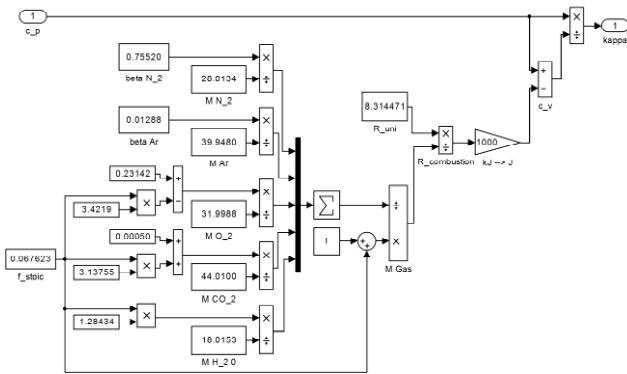


FIGURE 15. Implementation of the isentropic exponent

of the specific gas constant R_s . Except for missing components, this subsystem finally enables nearly all quantities of the simulation to be dynamic.

4. RESULTS

The results show the dynamic behaviour of the output quantities of the gas generator. Because of the missing components, the transient operations can be performed within small limits due to constant conditions in front and behind the gas generator. Additionally, the static operating point reached after 0.4s is not the design point of the IAE V2500 gas generator. The lower operating point is chosen to ensure a sufficient choke and surge margin of the HPC. This has been important due to the problems arising from the inadequate regressions at the beginning of the development.

The output quantities of the HPC, presented in FIGURE 16, show an operation towards the surge line. An increasing pressure ratio directly involves an increasing HPC outlet temperature. After 0.4 seconds a steady state operation is reached within the component map of the compressor. This means the HPC works within its limits and reaches an equilibrium state with the HPT.

During the acceleration of the gas generator, the HPT slightly decreases the mass flow passing the gas generator. This represents the characteristics of the HPT, which has the feature of decreasing mass flow while the spool speed increases. Please note that in FIGURE 14, the true mass flow is plotted against the time instead of corrected HPT mass flow.

In comparison with the reference simulation in GasTurb,

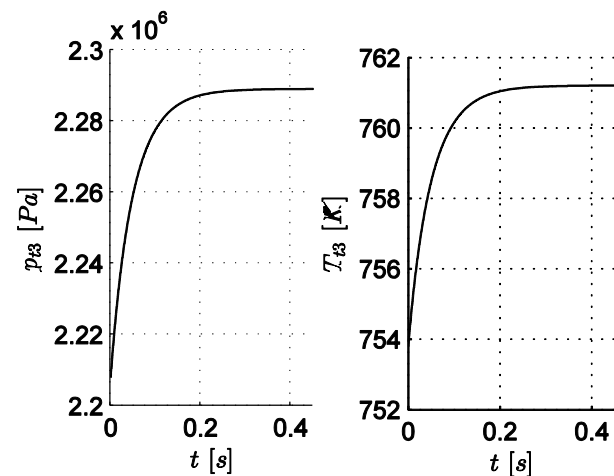


FIGURE 16. High pressure compressor simulation results

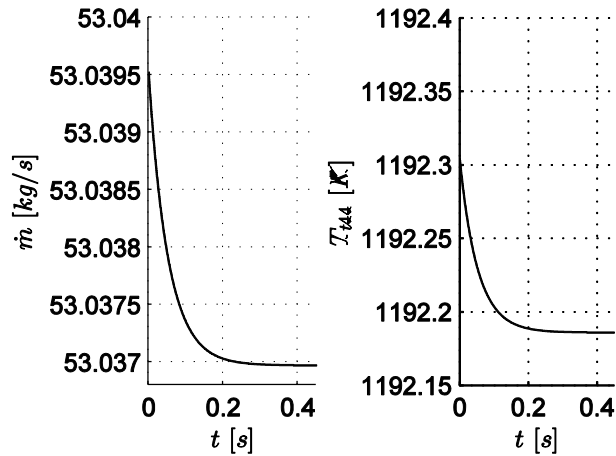


FIGURE 14. High pressure turbine simulation results

the steady state operation point of the Simulink model differs slightly. The maximum difference in per cent remains below 1.82% and occurs at the HPT outlet temperature T_{t44} . In TABLE 1, the steady state output quantities are compared to the GasTurb reference simulation of the high pressure system.

As presented in TABLE 1, most of the output variables are greater than the reference values. This is due to the fact that the combustion chamber is simulated by a constant HPT inlet temperature. Therefore, a stoichiometric combustion is assumed, which leads to a higher fuel to air ratio in comparison to the reference. High fuel to air ratios find expression in high isobaric heat capacities downstream of the combustion chamber. Due to the high isobaric heat capacities, the calculated thermodynamic power, which is converted to shaft power, is too high. This forces the high pressure system to accelerate towards higher angular speeds. At higher speeds, the high pressure turbine slightly decreases the processable mass flow. The combination of a lower mass flow and higher angular speed forces the HPC to work at an operating point towards the surge line, which leads to higher HPC outlet temperatures and pressures.

	GasTurb Reference	Improved regressions method with variable gas properties	
	Absolute quantities	Absolute values	Relative deviations
ω	1312.87 rad/s	1321.61 rad/s	+0.67%
\dot{m}	53.05 kg/s	53.04 kg/s	-0.02%
P_{t3}	2.252 MPa	2.289 MPa	+1.64%
T_{t3}	758.79 K	761.21 K	+0.32%
T_{t44}	1170.87 K	1192.19	+1.82%

TABLE 1. Comparison of steady state results

5. CONCLUSION

The model, which is implemented in Simulink, is able to perform transient operations. The resulting output quantities show that the implemented component map read-out methods and the set of equations lead to a reliable steady state operation, compared to the reference simulation.

Due to the not-yet-implemented low pressure section, bypass stream, nozzle, and combustion chamber, it is mandatory to model these modules in the next development steps. The low pressure compressor and low

pressure turbine are easily implemented by using the modelled high pressure components and replacing the high pressure component maps by low pressure component maps. Since the variable gas properties are implemented in the HPC, the correct fuel to air ratio can be passed to the HPC after the implementation of the combustion chamber. Finally, the nozzle, fan and bypass section should be implemented to be able to simulate the dynamic behaviour of the whole engine and compare it to test bed runs.

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