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# VALIDATION OF A MIXED FLOW TURBOFAN PERFORMANCE MODEL IN THE SUB-IDLE OPERATING RANGE

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## ABSTRACT

During turbofan development programs the evaluation of steady-state and transient engine performance is usually achieved by applying full thermodynamic engine models at least in the operating range between idle and maximum power conditions, but more recently also in the sub-idle operating range, e.g. for steady-state windmilling behavior and for starting, relight and shut down scenarios.

The paper describes the setup, and in more detail the validation, of a full thermodynamic engine model for a two-spool mixed flow afterburner turbofan which is capable to run from maximum power down to zero speed and zero flow conditions in steady-state and transient mode. The validation is performed by using the model-based performance analysis procedure called ANSYN even in windmilling operation. Once the steady-state sub-idle model is validated the extension to transient sub-idle capability is achieved by simply adding the effects of rotor moment of inertia of the spools, while heat soakage effects are rather negligible without heat release in the burner. Especially lighting conditions in the burner are produced by such a validated sub-idle model inherently due to reliable data calculated at the burner entry station.

The variety of applications of a validated full thermodynamic engine model is large. The performance data delivered is highly reliable and very consistent because the full operating range of the engine is covered with one model, and by appropriate means of speeding up the calculation even real-time capability may be achieved. In the paper synthesized data for an engine dry crank is compared to real engine test data as one typical application.

## NOMENCLATURE

| | |
|---|---|
| $A$ | area |
| $F$ | thrust |
| $\Delta h$ | specific work |
| $H$ | flight altitude [km] |
| $M$ | modifier |
| $Ma0$ | flight Mach number |
| $NH$ | HP spool speed |
| $NL$ | LP spool speed |
| $P$ | total pressure |
| $PS$ | static pressure |
| $T$ | temperature |
| $\Delta T0$ | deviation from standard day temperature [K] |
| $W$ | mass flow |
| $WC$ | customer bleed flow |
| $WF$ | fuel flow |
| $\delta$ | $P2/101.325$ kPa |
| $\eta$ | efficiency |
| $\Pi$ | pressure ratio |
| $\Theta$ | $T2/288.15$ K |

### Abbreviations

| | |
|---|---|
| HP | high pressure |
| HPC | high pressure compressor |
| HPT | high pressure turbine |
| LP | low pressure |
| LPT | low pressure turbine |
| POT | standard corrected power offtake POT$/\sqrt{\Theta}/\delta$ [kW] |
| RNI | Reynolds Number index $\delta/\Theta^{1.15}$ |
| SAS | secondary air system |
| SLS | sea level static |

## 1 INTRODUCTION

The use of full thermodynamic models for the prediction and analysis of engine performance in the range between idle and maximum power is state of the art for a long while. The performance calculation tools are thereby usually modular structured and synthesize the performance of the engine based on the characteristics of its individual components. Using these tools a full thermodynamic model of nearly any engine configuration

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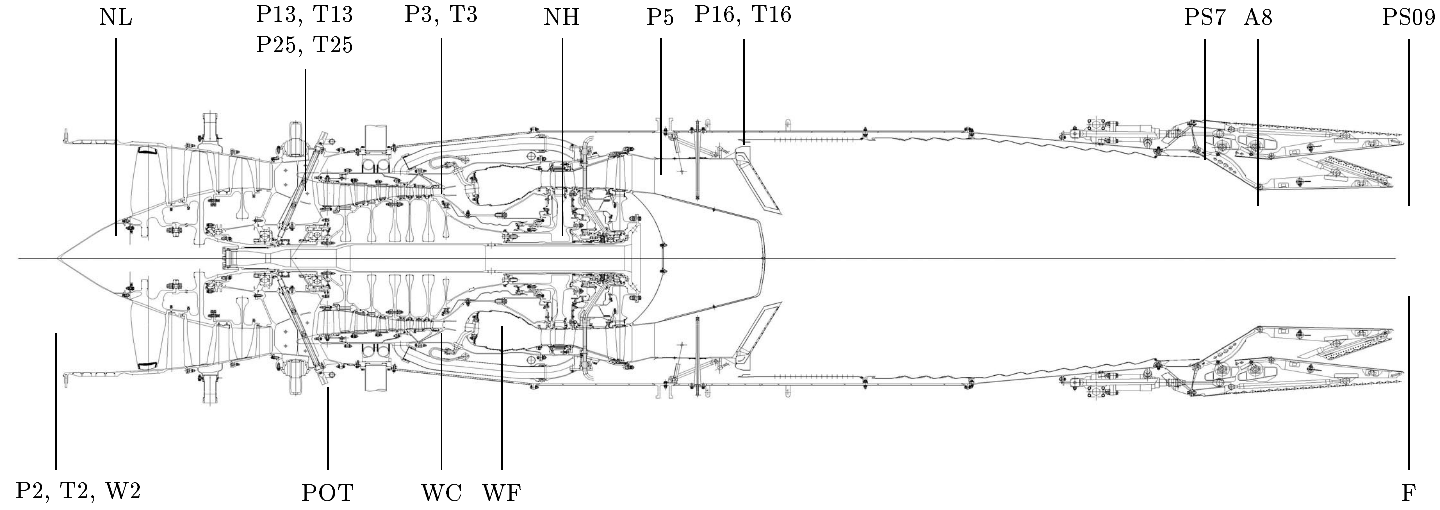

**Figure 1: General arrangement of the reference engine including typical instrumentation**

can be set up, which allows the calculation of the steady-state and transient engine performance with sufficient accuracy.

Besides the normal operating range between idle and maximum power there are several applications which request the calculation of the engine performance in the sub-idle range. As far as the airframer is concerned the drag of the engine and the maximum possible power and bleed offtake under windmilling conditions are important inputs. The engine design is affected e.g. in terms of the windmilling spool speeds which have to be taken into account for the mechanical design of the rotor, and in terms of burner ignition capability being relevant for the burner primary zone volume. Furthermore the transient engine performance is of importance, e.g. for the determination and optimization of fuel flow and bleed schedules during engine start, for the calculation of shut-off, flame out and auto relight scenarios and for the prediction of the maximum spool speeds in case of a shaft break event, see [2], [4] or [5].

For the calculation of sub-idle performance often simplified models are used. The shortfalls of these models are a considerable lack of accuracy compared to the full thermodynamic models and the fact that they are usually not covering all relevant applications. Thus usually at least two different performance models are necessary during one engine development program. Therefore the use of full thermodynamic models even in the sub-idle range is advantageous, enabling the use of one single model for the continuous representation of the engine performance from zero speed up to maximum power.

The quality of the predicted sub-idle performance of course depends on the reliability of the model assumptions. Therefore it is important to validate the performance model not only in the normal operating regime but also in the sub-idle range by a comparison of the predicted engine performance with real test data. Such a validated performance model will then support the engine development process with consistent and reliable performance data in the whole operating range of the engine.

## 2 SUB-IDLE MODEL SETUP AND VALIDATION

The sub-idle model setup and the validation procedure will be described using a two spool mixed flow afterburner turbofan engine with a convergent-divergent nozzle and a low design bypass ratio as an example. In Fig. 1 the general arrangement of the engine including a typical development engine performance instrumentation is shown.

Prior to any engine test a so-called pre-test model is established, which is based on measured or calculated component performance characteristics. Of course the engine performance has to be validated with engine test data. With the typical development engine performance instrumentation shown in Fig. 1 it is possible to evaluate the real in-engine characteristics of all major components, particulary of the turbomachinery. The validation procedure is carried out with the so-called ANSYN method (see Fig. 2), the basic idea of which is to match the synthesis model to real engine test data on a component level by introducing so-called modifiers. These modifiers can be used afterwards to calibrate the pre-test model in such a manner that the resulting so-called post-test model represents the real characteristic of the engine with high accuracy.

The basis of any sub-idle model is a validated full thermodynamic model for the normal operating range, which describes the steady-state performance of the engine including installation effects with high quality in various flight conditions and power settings. A synthesis model for the whole steady-state operating range including sub-idle can be generated among others by means of extrapolating component characteristics down to zero speed and zero flow conditions, see [7] or [9]. Extrapolating or any kind of calculation is necessary to generate component characteristics because usually rig test data are not available. This is due to the fact that typical in-engine windmilling operation takes place at component pressure ratios near or below unity thus not allowing to test appropriate conditions in ground test facilities. Conducting rig tests in an altitude test facility will increase costs significantly.

The extended model at first is calibrated and afterwards

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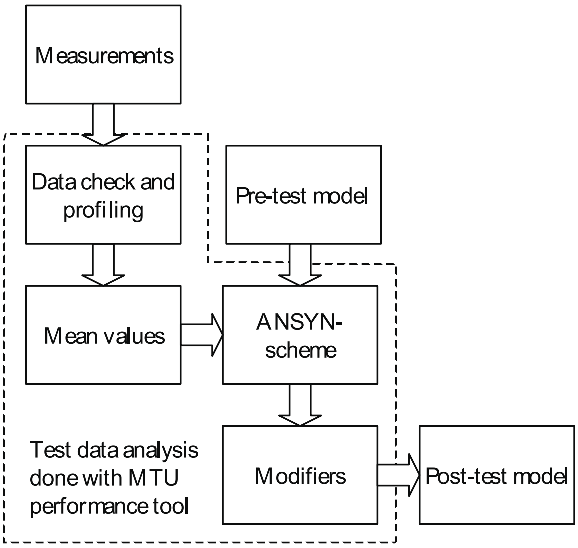

**Figure 2: Model adaptation process based on the ANSYN method, see also [3]**

validated by means of ANSYN against steady-state sub-idle test data, particulary against windmilling operating points with various ram pressure ratio, power offtake, customer bleed, etc.. The calibration is usually necessary because extrapolating methods do not provide sufficiently accurate component characteristics when compared to the upper operating range. So during the calibration step some modifications of component characteristics might occur because engine tests are used instead of usually not available rig tests to establish component performance in the sub-idle operating range.

Based on the validated steady-state model available for the whole operating range between zero speed up to maximum power a dynamic full thermodynamic model is produced by extending it to transient effects. In the sub-idle operating range the major effect is the rotor moment of inertia, while heat transfer might have a significant impact during light-up and the following speed-up to idle. A validation of the dynamic model in the sub-idle operating range is usually not neccesary because with correct numbers for the rotor moments of inertia and a proper aero-thermo model of the components the dynamic behavior of the engine is inherently generated.

## 3 MODEL SETUP

The sub-idle model is produced by extending a validated synthesis model down to zero speed and zero flow conditions. As the model is already validated in the range between idle and maximum power the extension on the one hand must not compromise the accuracy in this operating range, but on the other hand it has to allow for a suitable physical representation of the engine components in the sub-idle range.

### 3.1 Turbomachinery

A map representation of the turbomachinery based on efficiency or specific work is no longer appropriate for the sub-idle range as efficiency runs towards infinite values if the specific work becomes zero (for compressors) or the pressure ratio becomes unity (for turbines) respectively. The specific work is also a problematic parameter as it is always zero for zero speed. Hence, the torques produced by compressors and turbines in case of non-rotating rotors can not be derived from their specific work. For this reason the map representation is changed using corrected flow, pressure ratio and corrected torque as dependent parameters for both compressors and turbines, see e.g. [9].

Furthermore the turbomachinery characteristics have to be extended down to zero speed and zero flow conditions extrapolating their maps or generating them by some other means. For the map extrapolation there are several methods in use (see e.g. [7]). In this paper an extrapolation method is used based on the similarity laws for incompressible flow, as described in [9].

In the normal operating range between idle and maximum power several corrections based on efficiency are in use to take the influence of various second-order effects into account. As the efficiency is no longer an appropriate parameter in the sub-idle range these corrections should be eliminated and as far as possible be replaced by corrections on the pressure ratio or corrected torque respectively. However, as some corrections are aimed to be defined based on known changes of the efficiency, as e.g. for Reynolds Number or tip clearance effects, the resulting efficiency corrections must be kept to ensure the compatibility of the extended model with the normal operating range. The numeric algorithm of the above mentioned corrections — calculating the pressure ratio from the given specific work and the corrected efficiency — is still valid for the sub-idle range for the most operating conditions. So the efficiency corrections can be used even in the sub-idle range, which does not necessarily mean that the resulting numbers indeed represent the real physical correlations in this operating range. Only if the specific work becomes zero the correction algorithm fails as the efficiency is no suitable parameter to relate specific work to pressure ratio for $\Delta h = 0$. In this case the above mentioned corrections cannot be applied. Beyond that all correction algorithms should be checked carefully whether they still produce physically reasonable results in the sub-idle range, as e.g. the Reynolds Number correction tends to produce infinite corrections if the flow approaches zero.

The energy transfer between the compressors and turbines mounted on the same rotor is usually calculated using the power balance of the rotor. As stated above the specific work and hence the power of the turbomachinery is always zero for zero speed while the torque does not need to be zero. Therefore the power balance must be replaced by a torque balance to enable calculations of a blocked rotor. Consequently the contribution of extracted flows to the power of a compressor must also be formulated using torque.

### 3.2 Secondary Air System

The flow extraction into the SAS is often modelled by a constant corrected flow at the flow source ([10]). This is not an appropriate model for the sub-idle operating range as the pressures and temperatures are still finite numbers while the flow and hence the corrected flow tend to be zero when approaching zero speed. Therefore the modelling of the SAS flows is adapted e.g. by using constant relative SAS flows or relative SAS flows

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as a function of corrected compressor inlet flow respectively. In this case the sub-idle model differs from that one of the upper operating range and a special treatment of the transition for the two ranges is needed to keep the upper one unchanged.

In case of no heat addition in the burner as for example in steady-state windmilling operation the SAS flow temperatures do not deviate significantly from the turbine stator outlet temperature. Therfore an erratic amount of SAS flow hardly influences turbine and thus engine performance.

### 3.3 Burner

The heat release in the burner in the upper operating range is dominated by a reaction controlled burner system and burner efficiency can be described as a function of the burner loading, e.g. by the air loading parameter, see [11]. This model is insufficient for the sub-idle range where heat release is increasingly dominated by a vaporization controlled burner system. Hence, the burner efficiency model is extended for the sub-idle range taking into account the correlations of a vaporization controlled burner system (see e.g. [8]).

For modelling the burner the limits for ignition and flame out have to be established in the performance model. In open literature one can find somewhat generic data for these limits, e.g. in [11] the boundaries for rich and weak ignition as well as for rich and weak extinction in a diagram with the equivalence ratio versus burner loading are shown. This data is adapted for the particular engine model by fitting the geometric properties to the real burner design.

### 3.4 Accessories Power Demand

Engine accessories such as fuel pumps, oil pumps and hydraulic pumps are mechanically linked to the turbo components under windmilling conditions, too. The power needed to drive them related to the power transferred by the rotor is thereby much higher than in the normal operating range. Therefore the power consumption of the accessories has to be modelled with care in the sub-idle range due to the increased influence on engine performance. If for zero speed the accessories produce non-zero torque, the latter has to be included in the torque balance of the blocked rotor. So again, the formulation of a power demand is insufficient and should be replaced by a torque demand.

### 3.5 Gasdynamics

In all engine components the Mach Numbers in the sub-idle range and especially when approaching zero flow tend to be zero, too. This is especially true in and downstream of components with heat addition in the normal operating range but without heat addition in the sub-idle range, such as unlit burners, turbines, reheat systems and nozzles. This situation requests very robust models calculating the gasdynamic correlations which show zero or infinite gradients with Mach Number approaching zero.

### 3.6 Numerics

The equations of conservation of continuity and energy are usually solved iteratively in a full thermodynamic model. The relative error definition — relating the difference of two calculated numbers to one of them — is thereby not suitable for the sub-idle range as the flow as well as the power or the torque respectively may become zero. Whereas this problem can be solved for the continuity equation simply by adding a constant number to the flow, it is not as easy for the energy equation as the power may become negative in the sub-idle range. Therefore the reference value has to be limited or must even be a fixed number, which will produce either bends in the error function or a changed relative accuracy in the normal operating range.

For the solution of the global iteration scheme in turbofan engine models the bypass ratio is often used as an independent parameter. Approaching zero flow this parameter is not defined any more and hence cannot be used. Therefore the bypass ratio has to be replaced by a parameter which describes the split between core and bypass flow as well and which is defined even for zero flow, e.g. the HPC corrected flow.

### 3.7 Application

As the major result of the model setup procedure the calculation of various engine working lines in the normal operating range and in windmilling conditions is possible with one single synthesis model. As an example in Fig. 3 an engine working line for SLS conditions is shown between idle and maximum power in the HPC map. The windmilling working line for zero power offtake and zero bleed, which was calculated with the same synthesis model, can be seen in addition.

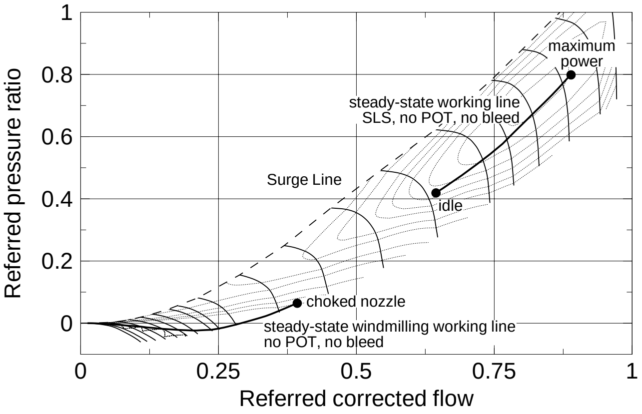

**Figure 3: Calculation results provide by one single synthesis model shown in the HPC map**

## 4 MODEL CALIBRATION AND VALIDATION

### 4.1 Model Based Analysis

The analysis of test data and the model validation in the normal operating range is usually done by a model based analysis procedure called ANalysis by SYNthesis (ANSYN), see [1], [3] and [6].

On the one hand ANSYN calculates all data which is not directly measured, e.g. thermodynamic variables of state in engine stations such as turbine inlet temperature, component performance parameters such as efficiencies and overall engine parameters such as bypass ratio or net thrust. On the other hand ANSYN includes the assumptions of the component characteristics derived from the pre-test model. So in addition to a pure test data analysis with ANSYN a comparison between the real data and the assumed component characteristics is performed. The way the comparison is done allows to consider the components almost seperately from each other and thus matching effects are nearly eliminated. The deviations between real and assumed component data are characterized with so-called modifiers which can be adders or scalers. In the normal operating range for the turbomachinery the modifiers for

$$\begin{array}{llcll}
\text{flow} & M_{\frac{\mathrm{W}\sqrt{\mathrm{T}}}{\mathrm{P}}} & = & \dfrac{(\frac{W\sqrt{T}}{P})_{\text{analysed}}}{(\frac{W\sqrt{T}}{P})_{\text{model}}} & , \\
\text{pressure ratio} & M_{\pi} & = & \dfrac{\pi_{\text{analysed}}-1}{\pi_{\text{model}}-1} & , \\
\text{efficiency} & M_{\eta} & = & \dfrac{\eta_{\text{analysed}}}{\eta_{\text{model}}} & \text{or} \\
\text{specific work} & M_{\Delta\mathrm{h}} & = & \dfrac{\Delta h_{\text{analysed}}}{\Delta h_{\text{model}}} &
\end{array}$$

are usually used.

By applying the modifiers to the pre-test model a post-test model is produced which represents the measured engine performance in a very good manner and is based on physically meaningful methods. The modifiers can be applied either within the performance calculation or prior to it to the input data itself, for example to the turbomachinery characteristics.

## 4.2 Application Of ANSYN In The Sub-Idle Range

In principal the ANSYN methodology is applicable to the sub-idle range in exactly the same manner as in the normal operating range. However there are some challenges which occur especially in the sub-idle range and which have to be taken into account in order to generate proper results.

### 4.2.1 Quality Of Measured Data

When analysing data gained from engine tests the uncertainty of the measurements has always to be taken into account. Especially when engine tests are performed in sub-idle (for example windmilling relight tests) and in the normal operating range using the same sensors, the pressure and temperature tappings have to be appropriate for a wide range of pressure and temperature levels. Usually the uncertainty is given by an absolut number (or percentage of full scale), which remains nearly constant for the whole operating range resulting in rather low relative uncertainties in the high pressure and temperature range and higher relative uncertainties at sub-idle conditions. This means that sub-idle data from an engine test is potentially more uncertain than data gathered at high power.

The situation gets even worse when taking into account that the component performance parameters, in particular specific work, are much smaller in sub-idle and thus measurement uncertainty will affect significantly the analysed parameters.

On the other hand in the sub-idle operating range the radial and circumferential pressure and temperature profiles are much less pronounced due to the much lower aerodynamic loading of the turbomachinery blading. Consequently when profiling the data it is easier to find outlying tappings by comparing the measurements of the individual sensors and to establish reasonable thermodynamic mean values.

### 4.2.2 Core Flow Analysis

When analysing test data gathered on mixed flow turbofan engines one challenge is always the core flow analysis. The core flow is usually not measured separately but has to be calculated on the basis of a known HPT capacity (turbine capacity method) or on the basis of a measured core exit temperature (heat balance method), see [1]. Both methods implicate problems in the sub-idle range. The HPT is not choked while the HPT flow characteristic is only known approximately from an extrapolation or calculation method. The core exit temperature is very close to the HPC inlet temperature without heat addition in the burner. Thus the flow split between core and bypass can hardly be determined with either of these methods.

### 4.2.3 Pressure Ratio Split Between HPT And LPT

A similar problem arises when P45 is not measured and the HPT efficiency is analysed on the basis of a given LPT capacity. Again the LPT is not choked in sub-idle and the LPT flow characteristic is extrapolated or calculated, still it is not known precisely.

### 4.2.4 Definition Of ANSYN Modifiers

The definition of the usually used ANSYN modifiers according to chapter 4.1 imposes another challenge. In case of the model parameter tending towards zero the scaler tends to be numerically sensitive because of division by a very small number or even by zero.

For flow this problem is acute only in very low sub-idle conditions, for example below ram pressure ratios of 1.01, because even small ram pressure ratios result in noteworthy flows. More problems occur with scalers based on specific work (or corrected torque) and pressure ratio. Here the specific work (or corrected torque) and $(\pi-1)$ run through zero in normal windmilling operation. Thus in windmilling analysis it is quite normal that these scalers become numerically sensitive.

### 4.2.5 ANSYN Procedure Managing The Challenges

Usually during engine tests no special instrumentation for sub-idle conditions can be used, so the analysis has to be performed with rather high sensor uncertainties. Thus careful profiling and checking of the measured data is of major importance. The filters used to detect outlying tappings should be set much closer to one due to the less pronounced profiles.

As far as the core flow analysis is concerned alternatively the HPC characteristic should be used to establish the core flow. HPC rig tests are usually performed down to aerodynamic speeds of 40% or even less while windmilling operation takes place nearly up to comparable speeds. Of course an HPC rig test in a ground test facility is not qualified for producing data below pressure ratio of one as already stated in chapter 2. But extrapolating HPC data from a ground test facility at 40% speed to pressure ratios around 0.9 or 0.85 is possible on the basis of flow physics, see [9].

In case of windmilling conditions with high ram pressure ratios the aerodynamic speed of the HPT is rather high due to the low T4 without heat release in the burner, so extrapolation of efficiency does not lead far beyond the characteristic tested on the rig. Thus when analysing windmilling conditions with

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high ram pressure ratios the HPT efficiency characteristic may be believed and the LPT capacity may be deduced. The LPT typically runs at much lower aerodynamic speeds and thus the deduced capacity establishes a reliable help for extrapolating the LPT map down to low speed.

As far as the ANSYN scalers are concerned adders instead of scalers should be used in the numerical calculation and scalers may be evaluated after the calculation. When interpreting the results the numbers should be carefully looked at keeping in mind that the scalers can become very sensitive.

## 4.3 Results

### 4.3.1 Calibration

Starting point of the calibration step is a pre-test model which consists of purely extrapolated component maps. Two windmilling conditions gathered for one engine build on one testbed for two different ram pressure ratios without power offtake and customer bleed were analysed with the help of ANSYN. The derived modifiers are used to calibrate the characteristics of the components, in particulary of the turbomachinery. During calibration one has to ensure that the flow physics keep represented. The result of the calibration step is a post-test model based on improved component characteristics and thus representing the real engine characteristics with high accuracy, at least for the two calibration conditions. In case of the calibration step being performed with appropriate care the resulting accuracy is comparable with typical numbers in the normal operating range.

### 4.3.2 Validation

As the calibration step is performed for two windmilling conditions only the post-test model still has to be validated.

**Table 1: Conditions for the analysed windmilling scans**

| $H$ | $Ma0$ | $\Delta T0$ | $\frac{P2}{PS0}$ | POT | $\frac{WC}{W25}$ [%] | RNI | Mark |
|---|---|---|---|---|---|---|---|
| **Engine Build #1** | | | | | | | |
| 1.5 | 0.41 | 2.4 | 1.12 | 0.34 | 0 | 0.93 | □ |
| 1.6 | 0.42 | 1.8 | 1.12 | 0.38 | 0.66 | 0.93 | □ |
| 1.5 | 0.46 | 1.9 | 1.15 | 0.38 | 0 | 0.95 | □ |
| 12.3 | 0.82 | 5.2 | 1.54 | 1.36 | 0 | 0.33 | △ |
| 6.9 | 0.89 | 3.2 | 1.67 | 2.00 | 0.38 | 0.70 | □ |
| 7.0 | 0.89 | 3.5 | 1.68 | 1.99 | 2.75 | 0.70 | □ |
| 7.0 | 0.95 | 2.2 | 1.76 | 13.1 | 0 | 0.73 | ▽ |
| 7.9 | 0.96 | 2.4 | 1.79 | 1.40 | 0 | 0.68 | □ |
| 7.0 | 1.10 | 1.6 | 2.12 | 31.4 | 0 | 0.82 | ▷ |
| 7.0 | 1.09 | 2.0 | 2.12 | 29.7 | 2.88 | 0.82 | ◇ |
| 15.3 | 1.21 | 2.0 | 2.43 | 4.88 | 0 | 0.29 | ○ |
| **Engine Build #2** | | | | | | | |
| 2.3 | 0.46 | 3.0 | 1.15 | 0.35 | 0 | 0.88 | □ |
| 6.9 | 0.60 | 4.0 | 1.26 | 0.75 | 0 | 0.59 | □ |
| 6.8 | 0.60 | 4.0 | 1.28 | 0.83 | 0.65 | 0.59 | □ |
| 7.6 | 0.90 | -0.3 | 1.69 | 1.82 | 0 | 0.66 | □ |
| 3.1 | 1.10 | 1.6 | 2.13 | 1.73 | 0 | 1.23 | ◁ |
| 3.1 | 1.10 | 0.5 | 2.13 | 22.6 | 1.35 | 1.24 | ◁ |
| 7.5 | 1.09 | 0.9 | 2.11 | 28.7 | 0 | 0.76 | ◁ |

Therefore ANSYN calculations were performed against the post-test model for a large number of windmilling scans gathered for two different engine builds on one testbed for various ram pressure ratios, with and without power offtake and customer bleed, and for various Reynolds Numbers. A list of all scans analysed and the corresponding conditions are shown in Table 1.

The accuracy of the post-test model can be proved by checking the resulting modifiers. To this end in Fig. 4, 5 and 6 the modifiers for fan bypass specific work, fan flow and HPC flow are shown for the windmilling scans specified in Table 1 and in addition for a variety of scans covering the operating range between idle and maximum power for comparison.

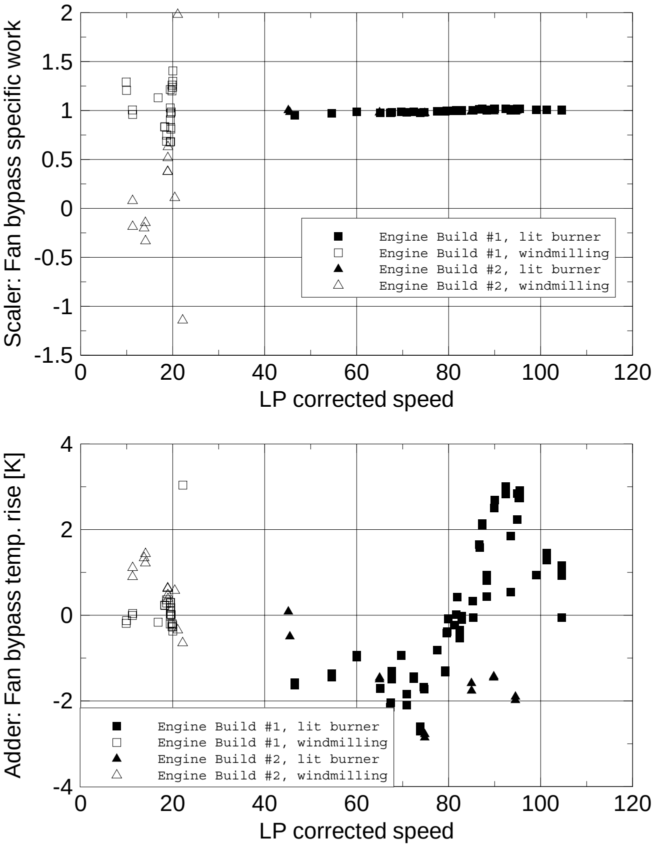

**Figure 4: Fan bypass specific work scaler compared to fan bypass temperature rise adder**

As already mentioned in chapter 4 the numerical sensitivity of scalers has to be kept in mind. In Fig. 4 it can be seen that as far as temperature rise and thus specific work is concerned the scalers are numerically quite sensitive and the validation is preferrably performed with the help of adders. On the other hand the flow scalers of the fan shown in Fig. 5 are numerically much less sensitive and the validation of the flow can be performed by either scalers or adders.

The distribution of the temperature adders and flow scalers show that there is no significant difference in the quality of the synthesis model between the sub-idle range and the normal operating range.

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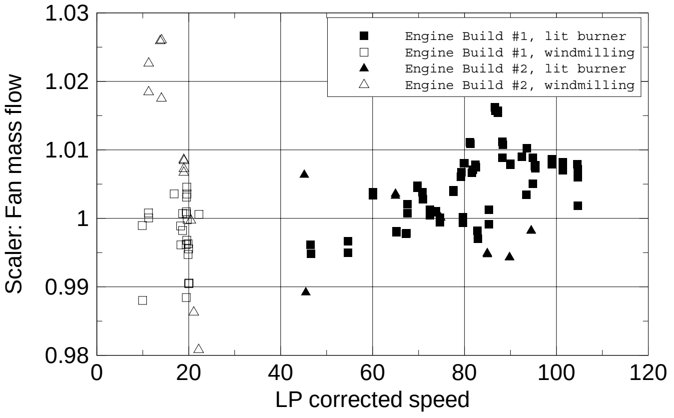

Figure 5: Fan flow scaler

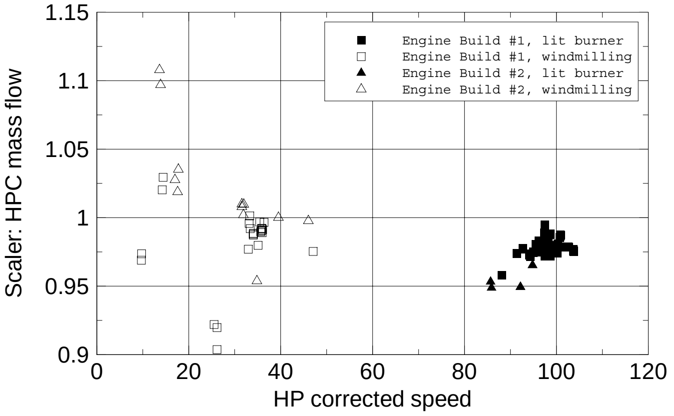

Figure 6: HPC flow scaler

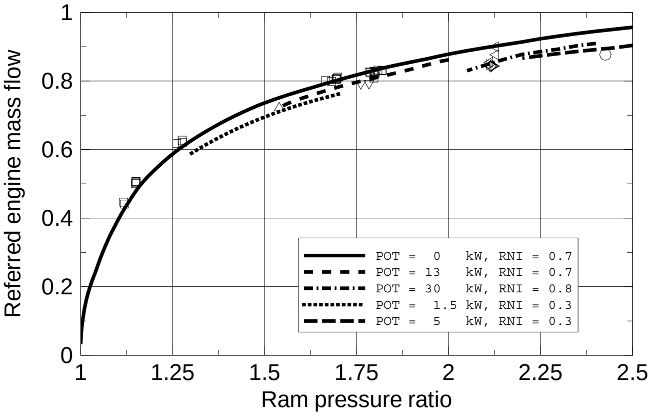

Figure 7: Referred engine mass flow versus ram pressure ratio

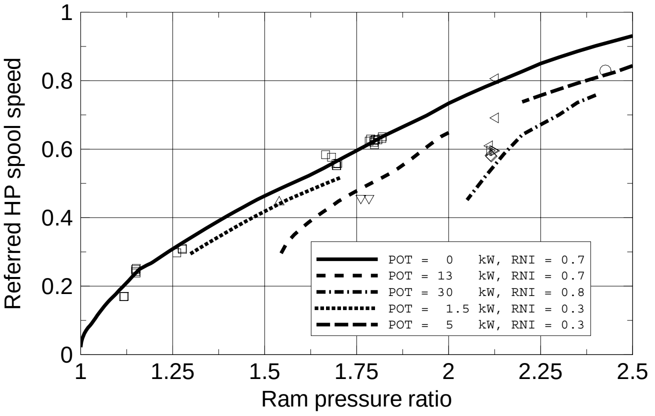

Figure 8: Referred HP spool speed versus ram pressure ratio

## 5 MODEL APPLICATION

With a validated full thermodynamic sub-idle capable engine model available a large variety of applications can be covered or supported respectively. This includes for example

- steady-state windmilling performance,
- transient sub-idle performance as dry cranks, ground starts, starter assisted and un-assisted windmilling relights,
- closed-loop propulsion system simulation.

In this paper results of the validated synthesis model are compared to real engine test data for steady-state windmilling operation and for an engine dry crank on a sea level testbed.

### 5.1 Windmilling

The validated synthesis model was used to calculate engine performance for the conditions listed in Table 1 including variations of ram pressure ratio, power offtake, customer bleed and Reynolds Number.

In Fig. 7 and 8 some typical results of the calculation are compared to real engine test data.

The marks used in the figures denote the test data and are associated with the scans according to Table 1. The curves represent the calculated data. The overall performance of the engine is characterized by the total engine flow which shows a very good agreement between measured and calculated data. Effects of power offtake, customer bleed and Reynolds Number on measured total flow are rather small, which is also confirmed by the model. In contrary the influence of these parameters on the core engine, which is characterized by high pressure spool speed in Fig. 8, is much larger. But again the model captures the measured effects very well.

### 5.2 Dry Crank

The validated synthesis model was extended by introducing the rotor moments of inertia thus building up a transient sub-idle model. This model was used to calculate engine performance during a dry crank on a sea level testbed with given inlet pressure and temperature, nozzle back pressure and starter torque.

In Fig. 9 the calculated results for HP and LP spool speed are compared to real engine test data versus time.

The calculated data in general show good agreement with the measured data. Especially the HP spool speed-up and the maximum achieved HP spool speed numbers are very close. The speed-up is mainly dominated by the starter torque so the positive result is not that surprising. On the other hand with increasing HP spool speed the power demand of HPC and HPT becomes more and more important. Taking this fact into account the results indicate that the turbo component maps in the rele-

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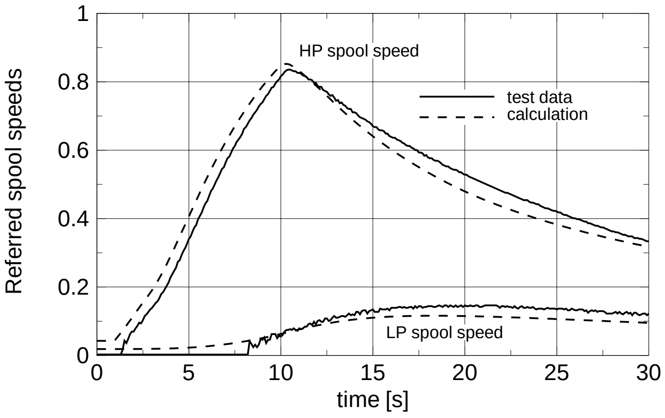

**Figure 9: HP and LP spool speeds for a sea level dry crank**

vant operating range are reliable. The LP spool speed speeds up with a time delay due to an aerodynamical link to starter torque only compared to a mechanical link of the HP spool speed. The time delay as well as the achieved numbers again are very close to the measurements.

The calculated spool speeds both do not start exactly at zero while the test data of course shows that number for the non-rotating rotor. This is due to the limited accuracy of any numerical calculation. The steady-state starting point of the dry crank calculation is found iteratively by a sequence of steady-state calculations with decreasing ram pressure ratio. At ram pressure ratio of 1.0 the solution is reached for the given accuracy for spool speeds which are slightly higher than zero.

## 6 CONCLUSIONS

This paper deals with the setup and validation of a full thermodynamic engine performance model for the whole operating range from start to maximum power. All the work is performed for a two-spool mixed flow low bypass ratio afterburner turbofan.

The model setup is achieved by extending a model validated in the high power range down to zero speed and zero flow conditions. To this end the turbo component maps have to be extrapolated and many other challenges concerning for example SAS modelling or numerics have to be met. The extended functionality is demonstrated by calculating steady-state working lines in the HPC map for idle to maximum power and for windmilling conditions with one single model.

The extended model which is based on purely extrapolated turbo component maps has to be calibrated to reach sufficient accuracy. To this end the ANSYN methodology is even applied to steady-state windmilling conditions. Some challenges evolving from that, as for example the core flow analysis method, are discussed in the paper and solutions are proposed. After calibration at two spot points the model is validated over a wide range of steady-state windmilling conditions with real engine test data. The resulting quality of the ANSYN method as well as of the model itself is comparable to the high power regime.

The validated model is used to calculate windmilling performance of the reference engine and, after extending it by rotor moments of inertia, for calculating a dry crank on a sea level testbed. The comparison with engine test data shows good agreement for both applications.

As the next step the extension of the burner model to enable calculation of light-up and speed-up to idle conditions is planned to be validated, which will finally close the last gap in accurately simulating engine performance from start to maximum power.

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