THE USE OF METHODS OF ARTIFICIAL INTELIGENCE IN APPROXIMATION OF CHARACTERISTICS OF A SMALL TURBOJET ENGINE MPM-20

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Presented article analyzes the possibilities of application of the ANFIS (Adaptive Network-based Fuzzy Inference System) on modelling characteristics of the small turbojet engine MPM-20. Its brief description is provided along with its capabilities in replacing currently used analytical models. Descriptions of selected MPM-20's characteristics (compressor and curve of joint operation of all components) are also provided. Speed altitude characteristic were calculated. For each of these characteristics several ANFIS systems were created and compared.

K e y w o r d s: small turbojet engine MPM-20, anfis, fuzzy, modelling, characteristic, compressor, approximation

1 INTRODUCTION

The purpose of mathematical modelling of aviation gas turbine engines is to enable us to reliably and precisely control them. Using these models we can also perform diagnostics of the engine itself or the sensors that measure engine parameters.

For the above described purpose it is necessary for the model to run in real time alongside the engine. Currently used system of analytical models calculated through m-files is computationally very demanding, because computer has to calculate many complicated equations. Demand for parallel running of the models requires all the engine parameters to be calculated every 0.01 of a second. Computer also has to convert measured data between the LabView environment and Matlab/simulink.

Aim of the usage of ANFIS (Adaptive network based fuzzy inference system) in engine modelling is to reduce the demand for computational power with minimal decrease in precision. ANFIS does not compute complex equations but rather it learns the relations between the input variables and corresponding outputs in the training data, therefore a significant performance savings can be achieved.

In this article the applicability of ANFIS on approximation of selected characteristics of small turbojet engine MPM-20 shall be verified. One section of the article, to each of the selected characteristics dedicated shall be.

2 COMPARISON OF ANFIS AND ANALYTICAL MODELS

Turbojet engine is a complex dynamic system with complex dependencies between its various parts. It is commonly modelled with analytical models. Analytical models describe complex system by using a set of mathematical equations that describe it. Such models are rarely perfectly accurate as they contain various simplifications to decrease their complexity and computing power demands.

ANFIS is a combination of fuzzy logic inference systems and neuron networks. Fuzzy logic enables ANFIS to approximate various nonlinear relations and uncertainties in the input data. Combining fuzzy logic and neuron networks makes it possible to set the parameters of the fuzzy inference system based only on knowledge of the relations between the input and output data. By doing so, we can eliminate disadvantages of one technology, by using the advantages of the other.

Main advantage of ANFIS over the analytical model is that we do not need to know or derive equations that characterize described system. Provided that we can measure input and output variables required to train the ANFIS. Properly trained ANFIS can quickly and precisely determine value of output. The increased speed is important if we want to run the model in real time because it allows us to free system resources for other tasks.

Main limitation of ANFIS is its poor flexibility compared to analytical models. ANFIS results are only valid if the evaluated inputs are not out of range of the inputs used in training.

Only one output ANFIS architecture allows, no matter how many input it has. Therefore for each engine parameter that we want to model a separate ANFIS is required. Analytical model on the other hand calculates all engine parameters.

3 MODELING MPM-20 COMPRESSOR CHARACTERISTIC USING ANFIS

Compressor characteristic shows how its total pressure ratio and efficiency change depending on its revolutions per minute and air mass flow rate.

3.1 Acquisition of ANFIS training and validation data

Before ANFIS can be used to model anything it needs to be trained. Training data in this paper was obtained using m-file provided by Ing. Ladislav Főző. This m-file was created in reference [4].

Inputs for training of the ANFIS will be the relative rpm parameter and mass flow parameter. ANFIS output will be the compressor’s overall pressure ratio.

The characteristic calculated in Matlab is shown on the Figure 1. Rpm range was set from 34000 to 50000 with step of 500 rpm. Range of the mass flow rate was set from 0.7 to 2.2 kg/s with 0.001 kg/s step size.

Validation data set was acquired the same way as training data with different rpm step of 325.

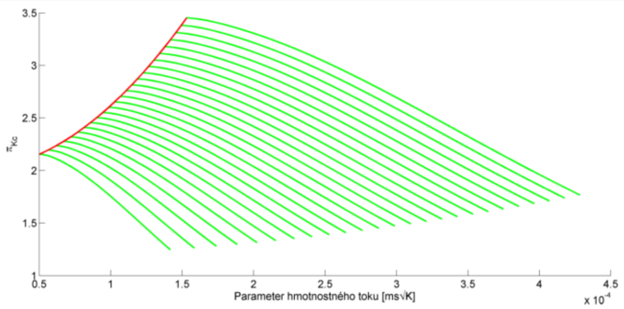

Figure 1 Compressor characteristic

Acquired data sets were converted to a matrix format required for the AFNFIS training data.

$$\left[n \frac{Q\sqrt{T_{1c}}}{p_{1c}} \pi_{Kc} \right]$$

This data was loaded through the "anfisedit" interface, where training method, type of FIS and number of epochs were selected.

Checking data was created by splitting the original data file in two matrices one for training data and the other for checking data. Odd rows were added to training data matrix and even to checking data matrix.

3.2 Characteristic in ANFIS

Several ANFIS systems were created and shall be evaluated in following text.

Systems had different count of membership functions from 5 per input to 10 per input. Selected membership function types were "gauss" and "bell". Defuzzification method was linear. These functions provided the best results during preliminary testing in Matlab. All these systems were trained with and without if checking data.

In table 1 evaluated ANFIS systems are compared divided according type of data used and membership function used. Comparison is made trough MAPE (Mean Absolute Percentage Error) and MAAPE (Maximum Absolute Percentage Error).

The best results achieved are highlighted in green.

Table 1 ANFIS comparison table

Without checking data					With checking data				
	bell		gauss			bell		gauss	
ANFIS typ	MAPE	MAAPE	MAPE	MAAPE	ANFIS typ	MAPE	MAAPE	MAPE	MAAPE
5x5	1.64	48.66	1.64	48.66	5x5	1.72	51.06	1.87	49.27
6x6	1.42	46.01	1.42	34.48	6x6	1.58	46.88	1.66	41.86
7x7	1.43	39.08	0.94	35.00	7x7	1.28	38.48	1.01	35.57
8x8	0.87	31.51	0.99	28.81	8x8	0.93	30.45	1.04	30.08
9x9	0.90	23.03	0.77	24.52	9x9	0.89	23.11	0.80	24.84
10x10	0.85	17.94	0.60	18.15	10x10	0.75	16.59	0.75	20.60

From the table 1 we can see that MAPE tends to decrease with increase of membership functions per input. Minimal value was achieved with 10 membership functions per input. For higher number of membership functions MAPE increased.

Average error from validation data was below 1 percent for the most precise ANFIS systems, which translates to absolute overall pressure ratio error of just 0.011.

Maximal error on the other hand is too high, over three times more than acceptable error of 5%. This translates to overall pressure ratio error 0.247. These high errors appear exclusively in low rpm area of the characteristic. Figure 2 clearly show the extent of these errors.

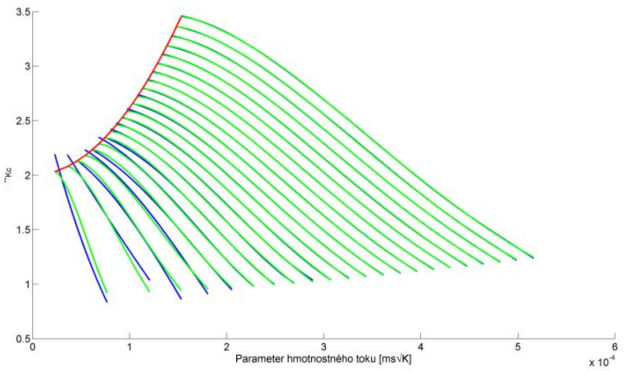

Figure 2 Comparison of calculated and approximated characteristic

Several methods were tried to remove low rpm inaccuracy, including using separate ANFIS for high and low rpm parts of the characteristic, adding a marker in the input data to distinguish whether rpm is high or low, reduction in the amount of training data, changing parameter of mass flow rate for actual mass flow rate. None of the above methods resulted in decrease of the maximal error to acceptable level.

Since the highest error appeared in the area of low compressor rpm the range of rpm for training was reduced to 38000 to 50000. This is a compromise solution as all the other attempts to decrease maximum error have failed.

Validation of ANFIS trained for lower rpm range with real values of mass flow rate had shown that MAPE has decreased to just 0.023% with maximum error of 0.175%. This means that absolute error of overall pressure ratio on average on fourth decimal place and maximal absolute error should not exceed 0.004.

4 APPROXIMATION OF CURVE OF STEADY OPERATION OF TURBOJET ENGINE MPM-20

4.1 Steady operation of turbojet engine

Turbojet engine comprise of intake, compressor, combustion chamber, turbine and nozzle. These parts are interconnected and their joint operation is only possible if certain conditions are met. The first of this conditions is that continuity equation has to be valid for all modes of engine operation. This means that mass flow rate through all engine components has to be constant. Second condition is the untwistability of the shaft connecting compressor with turbine.

From aviation engine operation perspective the most important modes are the modes during which rpm is constant. Such modes of operation are called steady because power required by compressor and accessories and power provided by turbine are in equilibrium.

4.2 ANFIS for approximation of steady operation of MPM-20

Training data were acquired with m-files provided by Főző L. and which were created as a part of reference [4]. These m-files calculate curves of joint operation and from them curve of steady operation of small turbojet MPM-20.

Three different sets of training data were created (rpm range 36243-49243) with different step size (1000, 500 and 250). Validation data set was created with same rpm range and step of 629 rpm.

Calculated values were transformed to matrix with format required by ANFIS. Input parameters were mass flow rate parameter of rpm. Output was overall pressure ratio of compressor during steady operation of engine. Mass flow rate parameter was not used because usage of real mass flow rate provided more precise results. Results of validation are in Table 2.

$$\left[Q_m \; \frac{n}{\sqrt{T_{1c}}} \; \pi_{Kc} \right]$$

Table 2 Validation results

	Type of function and training data used							
	Trimf 3x3 step n 1000	Trimf 3x3 step n 500	Trimf 3x3 step n 250	Trimf 4x4 step n 250	Trimf 5x5 step n 250	Gauss 5x5 step n 250	bell 5x5 step n 250	trap 5x5 step n 250
MAPE	0.08280	0.03880	0.03800	0.03390	0.03170	0.03630	0.04620	0.07320
MAAPE	0.61410	0.20170	0.19610	0.18170	0.16980	0.40080	0.33300	0.60820
MAAE	0.00830	0.00340	0.00290	0.00340	0.00270	0.00540	0.00450	0.00820
MAE	0.00140	0.00071	0.00069	0.00065	0.00062	0.00065	0.00085	0.00130

In the table MAAE is maximal absolute error and MAE is mean absolute error. Green highlights the best results achieved.

First ANFIS trained had 3 triangular (trimf) membership functions per input. It was trained with three different sets of training data to find out which training data would provide the best validation results. As we can see from the table the best results were achieved with training data set with step size 250 rpm. This data set was therefore used for all remaining ANFIS systems.

Afterwards systems with more membership functions were trained and systems with other types of membership functions were compared. The best result was achieved by ANFIS with 5 triangular membership functions per input.

5 APPROXIMATION OF ALTITUDE, SPEED AND THROTTLE CHARACTERISTICS

Speed characteristic shows thrust F and specific fuel consumption c_m as a function of flight speed v or Mach number. Usually altitude H and engine rpm are considered constant. For the purposes of this paper speed characteristic was calculated for different altitudes and rpm. Specifically the characteristics were calculated for:

H = 0 to 11 000 m with step 500 m
v = 0 to 250 m.s^{-1}
$\bar{n}$ = 0.8 to 1 with step 0.01

Maximal rpm for which relative rpm $\bar{n} = 1$ were 49400. Detailed description of characteristic’s calculation and characteristics themselves can be found in [8]. Characteristics used as training data were calculated according to this reference.

Example of a throttle characteristic calculated using this procedure is in the Figure 3. Such characteristic was calculated for all speeds and altitudes stated above.

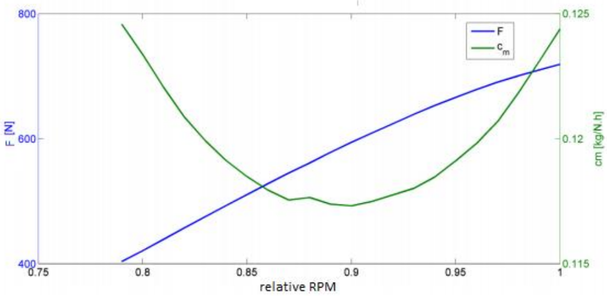

Figure 3 Throttle characteristic for H=0m v=0m/s

Calculated characteristics were once again converted to format required for ANFIS training. Separate systems were created for approximation of thrust and specific fuel consumption.

$$[n \; H \; M_H \; F]$$

$$[n \; H \; M_H \; c_m]$$

Validation data for altitude were created by adding 500 m to 250 m initial altitude until 10 750 m was reached. At the beginning and end of the altitude vector 0 m and 11 000 m values were added.

Vector of speeds was acquired using the “linspace” command in Matlab. Range of speeds was the same as for training data and step number was 35.

Validation rpm were acquired by changing rpm step to 0.0127. This should ensure sufficient difference between training and validation data sets. Validation data has been split to input data matrix and two vectors of expected outputs.

$$[n \; H \; M_H] \; [c_m] \; [\mathrm{F}]$$

Training data was loaded in the user interface summoned by “anfisedit” command. Two ANFIS systems with 5 triangular membership functions per input were created and validated. Validation results are in table 3.

Table 3 Validation for throttle characteristic ANFIS

	F[N]	cm[kg/N.h]
MAPE	0.09550	0.04770
MAAPE	2.88270	2.93530
MAE	0.32310	0.00006
MAAE	12.27120	0.00360

From table it can be seen that trained ANFIS systems have average errors well below 1 %, what means that average error in thrust is below 1N. Maximum error is almost 3% but that is most likely caused by sudden changes in validation data as can be seen on figure 3.

Average error in specific fuel consumption is also well bellow 1%, which means 60mg after rounding to 5 decimal places. For higher maximal error in specific fuel consumption the same applies as for the thrust error.

6 CONCLUSION

Analysis of trained ANFIS systems proved that ANFIS is capable of modelling jet engine characteristics. Accuracy of properly trained systems is very high.

Only major issue arose during training ANFIS for approximation of compressor characteristic, because ANFIS could not learn behaviour of the characteristic between 34 000 and 38 000 rpm. Because of this range of rpm had to be decreased to ensure acceptable accuracy of ANFIS model.

Validation of throttle altitude and speed characteristic has shown that it can be accurately approximated by ANFIS.

The most important factor in guaranteeing ANFIS precision was proper selection of training data. It is difficult to predict training results without prior experience with ANFIS training. That is why many systems were trained for compressor characteristic approximation. With gained experience smaller amount of systems was trained for approximation of next characteristics.

In the introduction was mentioned the requirement for reducing computational demands of used models to enable reliable calculation of engine parameters within the 0.01 sampling period. During validation of the ANFIS systems it was observed that evaluating ANFIS for all required input parameters took significantly less time than calculating them through m-files. For example calculation of curve of steady operation took several minutes while ANFIS evaluation took just few seconds.

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