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Evaluation of the Operational State of a Small Turbojet Engine Using Variations in Its Near Magnetic Field

L. Főző, R. Andoga*, M. Schrötter, K. Semrád, S. Szabo, R. Bréda, I. Vajdová and M. Spodniak

Technical University of Košice, Faculty of Aeronautics, Rampová 7, 041 21 Košice, Slovak Republic

Different parameters, which are obtained using classical sensors, are nowadays used to determine the technical state of turbojet engines. In order to expand and to improve this evaluation a novel idea in this area is presented that variations in the near magnetic field of an operational turbojet engine can contain valuable information about its state. Data analysis in different operational states of a small running turbojet engine is presented describing dynamical changes in magnetic induction in the near magnetic field in laboratory conditions. In order to detect the operational state of the engine using magnetic induction derivatives an infinite impulse response filter of the fourth order was designed with cut-off frequency of 2 Hz and expanded by a derivative element. The expanded filter was used to create a linear predictive model, which can be used to compute the rotational speed and exhaust gas temperature of a small turbojet engine using derivatives in magnetic induction in its near magnetic field.

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PACS/topics: diagnostics, magnetic induction, near magnetic field, turbojet engines

1. Introduction

Sensors directly placed in various parts of turbojet engines are usually used to observe and evaluate their technical and operational states [1, 2]. An array of hundreds of sensors is able to very precisely measure characteristics of turbojet engines and these parameters are used for their control and diagnostics [2]. In order to evaluate a technical state of different technical systems, variations in their near magnetic field have been studied [3]. Naturally this approach has been applied for electric engines and electric starter motors where the magnetic field is a part of their operational principle [3, 4]. In the area of diagnostics of turbojet engines, eddy currents were researched and a model was developed to create diagnostic information for blade vibrations [5]. The idea of using variations of magnetic induction in near magnetic field to obtain some additional information about a complex technical system like a jet engine, which is operating on thermodynamic principle is quite novel or unique and has been previously explored by the authors of the article [6]. It has been established that variations in the obtained frequency spectrum may hold some information about the rotational speed of a small turbojet engine. Further exploration of the time domain signals of the near magnetic field intensity of a small turbojet engine has therefore been performed to explore the possibilities of evaluation and prediction of certain engine parameters in time. Compared to the previous study another set of measurements has been performed on a small turbojet engine iSTC-21v and two basic state parameters of the engine were analysed. The question that is being explored is, whether the operational state of a jet engine can be predicted using variations of magnetic induction in its near magnetic field in the time domain. If a positive result is obtained, it can pave a way for more complex predictions in order to perform non-invasive diagnostics and detect some anomalies in operation of such high performance technical objects. The other area where this knowledge could be applied is to improve situational classification of operational states of turbojet engines.

2. Experimental setup

The measurements were done in the Laboratory of Intelligent Systems at the Faculty of Aeronautics of the Technical University of Košice using a small turbo-jet engine iSTC-21v with a proprietary control system design and a real-time data acquisition system [7]. The magnetic field was measured using the four channel VEMA-04 magnetometer [8, 9]. The engine installed in the laboratory is shown in Fig. 1 with the chosen arbitrary coordinate system. Three sensors of the magnetometer VEMA-04 were placed in the origin of the system designated as point O in the figure. This represents a point below of the turbine of the engine, where the greatest changes of the near magnetic field are expected. The individual channels of the magnetometer were placed in direction of the orthogonal axes designated as X, Y, Z and three sensors designated as $S_{x,y,z}$ [6]. This setup was expanded with another sensor S_w placed above the engine, measuring changes in magnetic field along the Z axis but above, designated as W.

*corresponding author; e-mail: rudolf.andoga@tuke.sk

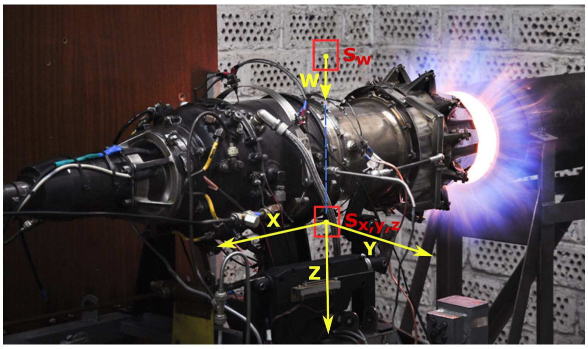

Fig. 1. The chosen coordinate system and sensor positions around the engine iSTC-21v.

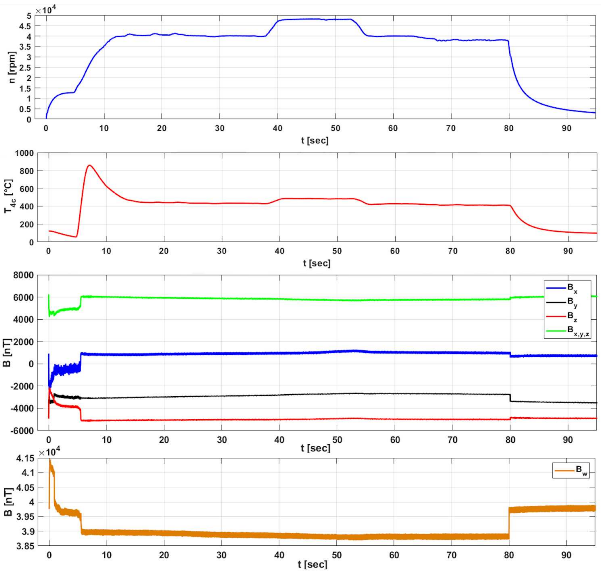

Fig. 2. Time course of magnetic induction measured during the operation of the engine. The measured parameters of the engine: n — rotational speed of the turbo-compressor [rpm], T_{4c} — total temperature on the turbine's outlet [°C], B_x — magnetic induction measured in the channel X [nT], B_y — magnetic induction measured in the channel Y [nT], B_z — magnetic induction measured in the channel Z [nT], $B_{x,y,z}$ — total magnetic induction computed as an absolute value of the x, y, z channels [nT], B_w — magnetic induction measured in the channel W [nT].

A digital real-time data acquisition system for the iSTC-21v engine is used to obtain standard operational parameters of the engine [7]. The main state parameters of the engine are its exhaust gas temperature T_{4c}, which is measured aft of the turbine and the rotational speed of the turbo-compressor n. These parameters are hypothesized to best correlate with changes in magnetic induction of the near magnetic field of the engine [6]. One experimental run showing these parameters is shown in Fig. 2. The engine is run for approximately 80 s, after spool up, the speed control system is engaged (time 30 s in the figure). The engine is then programmed to accelerate to 48,000 rpm and in its last stage of operation to decelerate to idle speed of 38,000 rpm with T_{4c} temperature reaching 800 °C. This covers nearly the whole operational range of the engine where the changes of magnetic induction in its near magnetic field are explored [5]. More information about the basic measurements of magnetic induction and engine parameters on a small turbojet engine can be found in [5, 6].

It can be seen in Fig. 2 that the total value of magnetic induction computed from the X, Y, Z channels changes around the value $B_{x,y,z} \approx 6000$ nT during operation of the engine. However, the signal is quite noisy [5]. A preliminary analysis has shown that the axis W holds more information about the state of the engine with $B_w \approx 3900$ nT. This channel was therefore used in the following analysis. A preliminary data analysis has shown that a filter needs to be designed and that the total value $B_{x,y,z}$ of magnetic induction cannot be related directly to speed or temperature of the engine. Therefore different type of analysis has to be done.

3. Time domain analysis

It can be seen in Fig. 2 that in time domain, changes in magnetic induction can hold some important information about the operational state of the engine. There are some sharp changes in magnetic induction, which can be detected. In order to detect these changes, derivatives need to be computed. In order to compute derivative, the noise in signal has to be attenuated by a filter. According the frequency analysis three Butterworth (BW) infinite impulse response (IIR) filters have been designed [10]. These are: a second order filter with low pass band up to 1 Hz $F_1(s)$ (1), a fourth order low pass BW filter at 2 Hz $F_2(s)$ (2), and a fourth order low pass BW filter at 3 Hz $F_3(s)$ (3):

$$F_1(s) = \frac{1}{0.02536s^2 + 0.2248s + 1}, \tag{1}$$

$$F_2(s) = \left(4.018e-05s^4 + 0.001319s^3 + 0.02164s^2 + 0.208s + 1\right)^{-1}, \tag{2}$$

$$F_3(s) = \left(7.937e-06s^4 + 0.0003907s^3 + 0.009618s^2 + 0.1387s + 1\right)^{-1}. \tag{3}$$

The applied filters can be seen in Fig. 3. The filter F_1 is dynamically the slowest one with highest total attenuation. In order to attenuate higher frequencies it is better to use two fourth order filters with a lower dynamic delay. They have been designed and are designated as F_2 and F_3. The filter F_2 has been selected as the best performing one.

In order to detect changes in magnetic induction in the near engine's field the filter's transfer function can be expanded by a zero giving the relation (4):

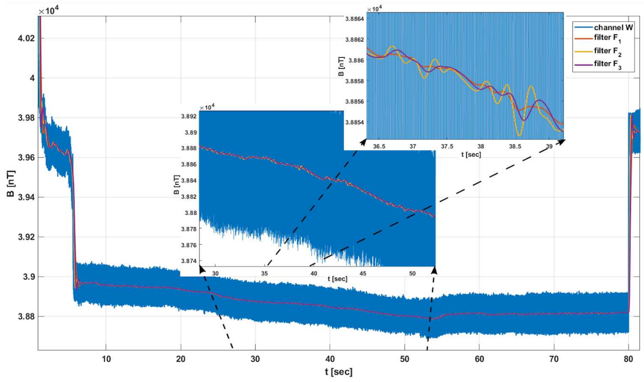

Fig. 3. Filtered time course of the magnetic induction changes during a single engine run.

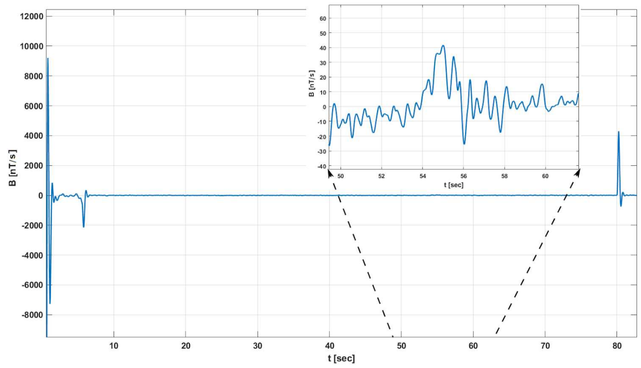

Fig. 4. Derivatives of the filtered magnetic induction along the W axis.

$$F_{2S}(s) = s\big(4.018e-05s^4 + 0.001319s^3 + 0.02164s^2 + 0.208s + 1\big)^{-1}. \quad (4)$$

The measured data, as shown in Fig. 3, is transformed using the derivative of the W element. The filter F_{2S} give the resulting signal, which highlights the biggest changes in magnetic induction of the near field as time derivatives, shown in Fig. 4 for a single run of the engine. The derivative can reliably detect the startup at 0 s, ignition at 5 s, and shutdown of the engine at 80 s of operation. In order to predict rotational speed or temperature of the engine the area during the deceleration of the engine at 50–65 s, highlighted in Fig. 4, has to be explored.

4. Predictive model

In order to determine the rotational speed of the engine or its temperature the computed derivatives of the magnetic induction can be used. When creating a linearized model, the derivative of magnetic induction divided by the derivative of the engine's rotational speed (5) or the engine's temperature (6) are given by

$$\Delta n(t) = \frac{\partial n(t)}{\partial B(t)} \Delta B(t), \quad (5)$$

$$\Delta T_4(t) = \frac{\partial T_4(t)}{\partial B(t)} \Delta B(t). \quad (6)$$

In order to obtain the derivatives $\frac{\partial B(t)}{\partial n(t)}$ and $\frac{\partial T_4(t)}{\partial n(t)}$, the data shown in Fig. 4 can be used by finding the maximum derivative of the engine's magnetic induction in a selected time frame and dividing it by the maximum derivative of the engine's speed or temperature in the selected time frame according to (7) and (8). A derivative in magnetic induction during operation of the engine was used at 55 s of the engine's operation, shown in the measurement in Figs. 2 and 4. Using this deceleration the following simple linear predictive model has been computed (7), (8):

$$\Delta n(t) = \frac{\mathrm{sgn}(\max|\partial n(t)|)}{\mathrm{sgn}(\max|\partial B(t)|)} \Delta B(t),$$

$$\Delta n(t) = \frac{-4532}{41} \Delta B(t) = -110.53 \Delta B(t), \quad (7)$$

$$\Delta T_4(t) = \frac{\mathrm{sgn}(\max|\partial T_4(t)|)}{\mathrm{sgn}(\max|\partial B(t)|)} \Delta B(t),$$

$$\Delta T_4(t) = \frac{-48}{41} \Delta B(t) = -1.171 \Delta B(t). \quad (8)$$

5. Conclusion

The results obtained from measurements using a small turbojet engine have shown that changes in magnetic induction in its near magnetic field hold information about its operational state in time domain. Data as measured by the magnetometer VEMA-04 have to be filtered in order to reliably detect and model dependence of the engine's parameters using changes in its magnetic induction. Three different suitable low-pass IIR filters have been analyzed with cut-off frequencies at 1, 2, and 3 Hz. It was found that a fourth order Butterworth-type low-pass filter with a cut-off frequency of 2 Hz is the most suitable one. This filter was expanded to filter raw data and directly compute derivatives of magnetic induction of a small turbojet engine (4). The computed derivatives were used to design a simple linear model in Eqs. (7) and (8) predicting the engine's temperature or rotational speed. In order to compute reliable and more complex models, more experimental data are needed.

Acknowledgments

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