ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1137917

INFLUENCE OF DIAGNOSTIC SIGNAL SAMPLING FREQUENCY ON ROTOR BLADE TECHNICAL CONDITION IMAGES DETERMINED FROM PHASE SHIFT DIFFERENCE

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Abstract

In the article, research results of rotor blades technical condition monitoring basing on special model φ_{T12T01} during operation are presented for various sampling frequencies. Method based on φ_{T12T01} model which is a difference of diagnostic signal y(t) phase shift resulting from blade operation and signal x(t) of its environment during blade tip approach to the sensor and its recession from the sensor. The assumed diagnostic model indirectly takes current blade environment x(t) into consideration without necessity of measurement.

Three out of 28 blades placed on first level of turbine engine compressor were analyzed. Research were undertaken in Θ_1 time for sampling frequencies of 500 kHz and 2 MHz. Results obtained for φ_{T12T01} model present the same technical condition (image) of blades.

The aim of this study is to present application of diagnostic model to rotor machine blades diagnostics during operation without necessity of measuring the environment signal as well as to prove that the method is correct for both smaller and greater sampling frequencies. Importance of this is a result of a fact, that sampling frequency increase requires more expensive, specialist equipment.

***Keywords**: turbine engine compressor, rotor machine blades, diagnostic model, phase shift difference*

1. Introduction

In the course of the use of the engine, according to service life (specified with a number of hours of passes) the actual level of fatigue of blade is usually unknown. This level mainly depends on the actual loads (centrifugal and aerodynamic forces), their values, character, frequency of occurrence in the period of use, etc., and also on that if there was a congestion, which in a short time could initiate micro-cracks in the material of the blades. These loads cause: stretching, two-sided bending and blade twisting, causing the blade material to fatigue conditioning durability. In addition, the complex shape makes it difficult to determine the degree of fatigue of compressor blades and make rational decisions about the continued operation of the engine [11].

In the process of the use of a turbomachine, monitoring the condition of each blade constitutes a very important problem. During its use technical condition, changes, until the emergence of very different defects (cracks, deformations, pittings, breaks of the portion of the blade) [5-8].

The main causes of these defects are material defects and machining process of the blade, the impact of foreign bodies and aerodynamic force caused by, for example, unstable compressor operation, inlet icing or retention of a foreign body in the engine inlet duct.

Currently, there are many different methods of diagnosing the technical condition of the blades at a standstill and during the operation of the turbomachine [5, 6, 8, 11]. These methods are based on knowledge of the object (blade), environment (working conditions of blades) and the information on the means of diagnosis.

Turbomachine blades diagnosis is carried out in two ways:

– in stationary conditions (diagnosis of non-rotating blades),
– in the turbomachine operating conditions (rotating blades diagnostics).

The diagnosis of blades in stationary conditions (when the machine is at a standstill) is based on studies of modal properties of the blades. A blade is stimulated to vibrate with a special model hammer or vibration inductor. The test results constitute the spectrum of vibration and resonance characteristics of the blades.

The diagnosis of blades in the operating conditions is a complex process within diagnostic testing (signals measurement) and in terms of diagnostic inference (signal processing into diagnosis). Diagnostic investigations of this method of diagnosis are based on the so-called 'non-contact' measurement of the current values of blade tip displacements at short times when it is in an area under the specialised sensor. A lot of „non-contact" measuring systems have been developed and implemented. These are commonly known and used measurement systems, manufactured by the following companies: Hood, Aqilis, Prat & Whithey (USA), Rolls Royce (UK), Turbochargers (Switzerland), MTU (Germany), and Russian, Chinese and Indian companies [2-4, 8, 9].

Well-known Polish non-contact measuring systems are also applied, especially those designed, built and implemented by the Air Force Institute of Technology (AFIT) in Warsaw.

Among the systems of non-contact measurement of blades displacement made by AFIT, the following items are listed:

- blade crack indicator: SPŁ-29 [6, 8, 11],
- indicator of excessive blade vibrations: SNDŁ-2b [6, 8, 11],
- microwave sensors: MUH, PIT [6, 8, 11].

Currently used sensors allow the measurement of linear displacement and angular blades of turbine engine, tip clearance, vibration and unbalance. They run on specific operating technical objects with great success (e.g., SO-3 engine).

A signal from the sensor resulting from the movement in front of the forehead of the blade sensor brings much needed information that can be used to assess its technical condition. Skilful experimental testing and application of appropriate signal processing methods in terms of determination of the condition of diagnosed blades allow for the obtainment of data needed for creating the basis for an effective method of diagnosis.

2. Measurement position

The tests were performed on a dynamometer of gas turbine engines in the Air Force Institute of Technology in Warsaw. The object of study is I level compressor blades (Fig. 1) of the axial turbine engine S0-3 mounted on TS-11 'Iskra' aircraft type.

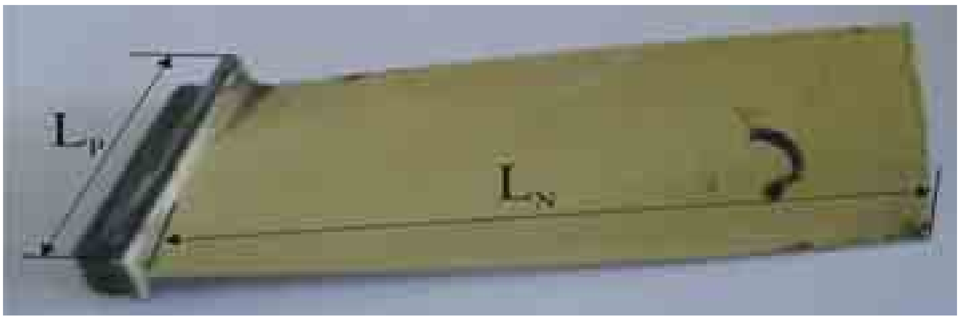

Fig. 1. I level compressor blades of the axial air turbine engine S0-3: L_N = 113 mm, L_P = 40 mm

To measure the movements of the blade, a non-contact inductive sensor was utilised (mounted permanently on the engine), it was designed and used by AFIT, Fig. 2. This sensor recorded the time and signal value of the instantaneous position of the tips of compressor blades during the engine operation when the blade was approaching and distancing from the detector [2, 4, 7, 9].

The signal from the sensor is recorded using specialised equipment and stored on a computer. The tests were conducted for the rotational speed of 6900 rpm.

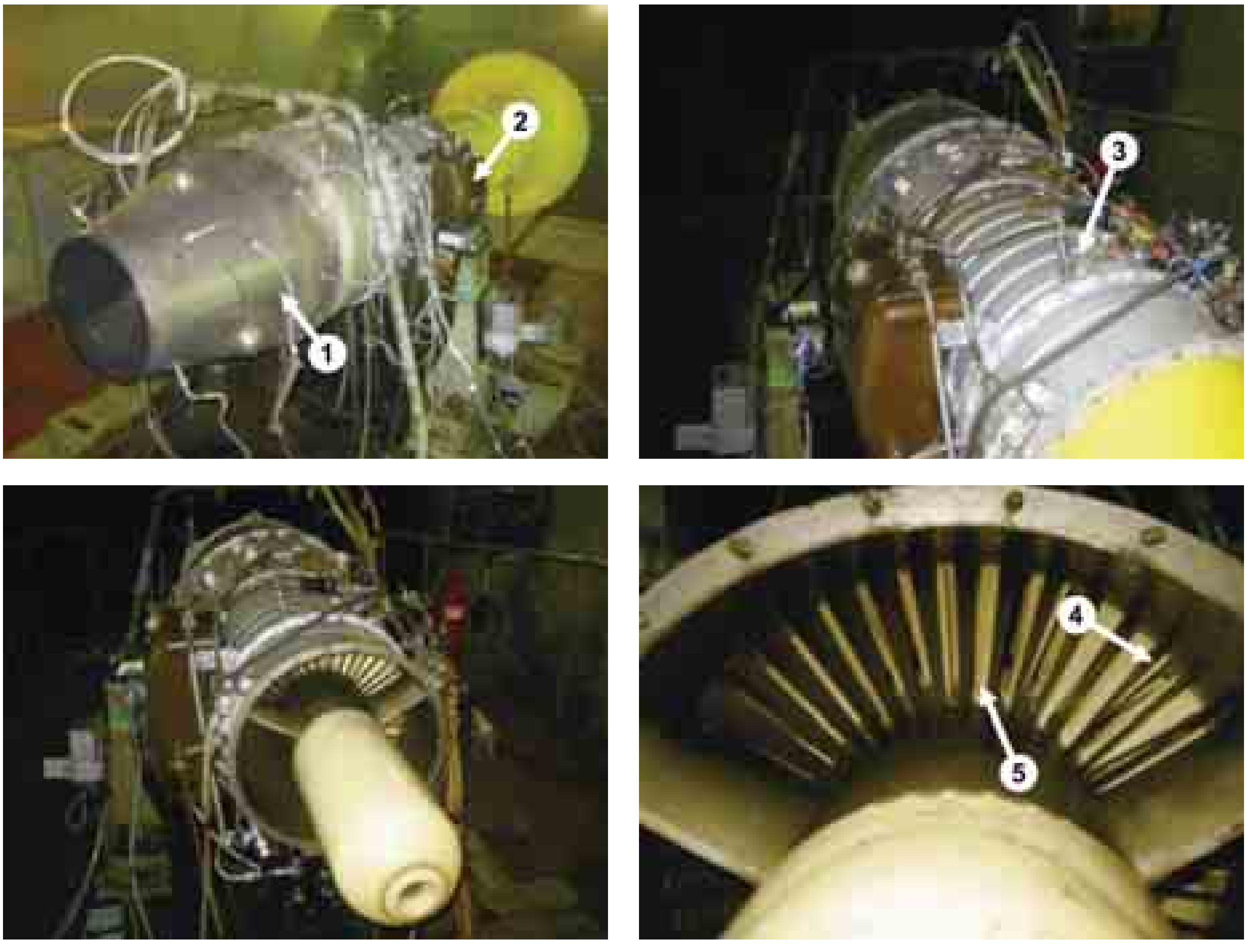

Fig. 2. Measuring station: 1 – turbine engine, 2 – measuring device, 3 – non-contact inductive sensor, 4 – compressor blades, 5 – guide blades

3. Theoretical basis for determining the φ_{T12T01} model

The problem of blade diagnosis during the turbomachine operation is very complex because, for the implementation of the diagnosis process of the blade, only one measurable and additionally distorted $y(t)$ signal and virtually immeasurable (except the n signals) $x(t)$ ambient signal are available. It is assumed that $x(t)$ surroundings will be represented by the distribution of $x(t) = \delta(t, \tau)$ [10].

The preliminary selection of the signal is introduced in order to separate a portion of the signal so that it could mirror a full migration of the blade under the sensor (from T_0 time to T_2 time).

Fixed T_{02} observation time (of T_{02d} and T_{02k} value) of the migration of $y(t)$ blade under the sensor [2, 4, 10] is appropriately divided into two periods: the approach of the blade to the T_{01} sensor and withdrawal of the tip from T_{12} sensor (T_1 moment corresponds to the situation when the tip of the blade is just under the sensor – Fig. 3). The adoption of a long T_{02d} or a short T_{02k} observation time of the blade (Fig. 3) arises from the need to fulfil the conditions for accurate processing of $y(t)$ signal to the $R_{xy}(\tau)$ cross-correlation function of the recorded $y(t)$ signal and the distribution of $\delta(t, \tau)$.

It is initially assumed that $x(t)$ and $y(t)$ are stochastic and disturbed timings. For the $y(t)$ displacement and distribution within the agreed periods of observation of T_{01} and T_{12}, cross-correlation R_{xy}^{*T01} and R_{xy}^{*T12} estimate functions are established and then analytical R_{xy}^{T01} and R_{xy}^{T12} expressions are matched to them [1, 10].

Then, the corresponding $S_{xy}^{T01}(\omega)$, $S_{xy}^{T12}(\omega)$ spectral power density functions are established. The presentation of $x(t)$ and $y(t)$ as $S_{xx}(\omega)$, $S_{xy}(\omega)$ functions will allow in a very simple way to describe the relationship between $y(t)$ diagnostic signals and $x(t)$ ambient signals for different periods of signal observation.

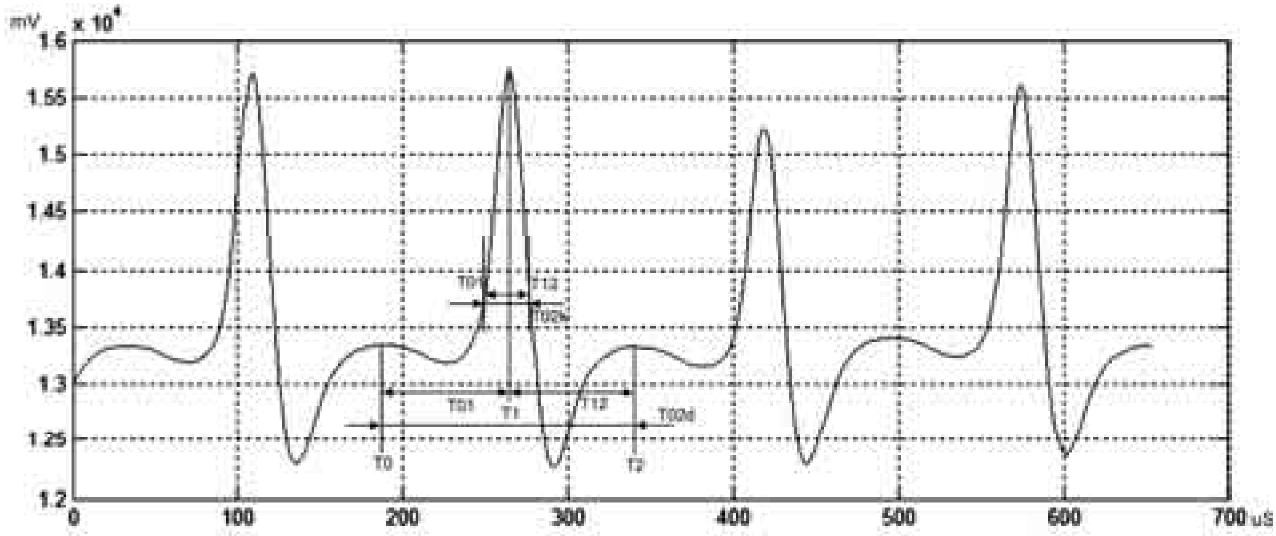

Fig. 3. Signal from the inductive sensor: T_{02d}, T_{02K} – respectively, long and short period of observation of a blade tip presence in the area of the sensor, T_0, T_1, T_2 – characteristic moments of observation of a blade tip under the sensor, T_{01}, T_{12} – sub-periods of observation of the blade tip respectively for T_d and T_k, mV – blade tip migration signal, μS – blade migration time

It is possible to record:

$$\varphi_{T01} = \text{Arg}\frac{S_{xy}^{T01}}{S_{xx}^{T01}},\ \varphi_{T12} = \text{Arg}\frac{S_{xy}^{T12}}{S_{xx}^{T12}}, \tag{1}$$

where:
φ_{T01} – phase shift of x and y signals at the time the blade approaches the T_{01} sensor,
φ_{T12} – phase shift of x and y signals at the time the blade moves away from the T_{12} sensor,
Arg – the main argument of the function.

Assuming that the observation period of T_{12} signal follows shortly (ms) after the observation of T_{01} signals, S_{xx}^{T12} and S_{xx}^{T01} signals are nearly equal. Following the 1 formulas and assuming that the environment e.g. $\delta(t, \tau)$ constitutes a high-power noise and that it can be correlated with $y(t)$ signal, it is possible to obtain a new abstract but physically interpretable value in the form of φ_{T01} and φ_{T12} phase shifts:

$$\varphi_{T12T01} = \varphi_{T12} - \varphi_{T01} = \text{Arg}\frac{\dfrac{S_{xy}^{T12}}{S_{xx}^{T12}}}{\dfrac{S_{xy}^{T01}}{S_{xx}^{T01}}} = \text{Arg}\frac{A_{T12}\,\mathrm{e}^{-j\varphi_{T12}}}{A_{T01}\,\mathrm{e}^{-j\varphi_{T01}}} =$$

$$= \text{Arg}\,A_{T12T01}\,\mathrm{e}^{-j(\varphi_{T12}-\varphi_{T01})} \xrightarrow{S_{xx}^{T12} \cong S_{xx}^{T01}} \text{Arg}\frac{S_{xy}^{T12}}{S_{xy}^{T01}}. \tag{2}$$

In this way, it is possible to set a new abstract diagnostic model (phase shifts difference), whose parameters carry the information about technical condition of a diagnosed blade [3, 6, 7]:

$$\varphi_{T12T01} = \text{Arg}\frac{S_{xy}^{T12}}{S_{xy}^{T01}} = Arg\frac{B_0 + B_1 s + B_2 s^2 + \ldots + B_5 s^5}{1 + A_1 s + A_2 s^2 + \ldots + A_5 s^5}. \tag{3}$$

Having relative A_i and B_i parameters determined, μ, σ, 2σ and 3σ (mean and standard deviation) can be calculated. Then, the determined deviations shall be indicated by „+" if relative value has exceeded σ, „++" if relative value has exceeded 2σ, „+++" if relative value has exceeded 3σ. In this way a portrait of the blade is received, which indicates the status of its usability. If there are numerous „+++”, they indicate a damaged blade, if „++”, they indicate an increased use of the blade, if „+”, they indicate a weak use.

This approach presents a clear and unambiguous picture of assessment of damage to the blade.

3. Influence of diagnostic signals sampling on the portraits of the technical condition of the blades

Three out of 28 blades mounted in a drum rotor were taken for the analysis. In the process of selection of blades, one blade had to differ from the remaining blades with regard to technical condition. The most damaged blade was selected – No. 1, slightly worn No. 11 and ‘healthy’ No. 3. The study was conducted at the time of Θ_1 for the rotational speed of 6900 rpm. The sampling rate for sensors was set to 500 kHz and then the tests were repeated for 2 MHz frequencies.

2000 cycles were generated from the course of a signal. Each cycle constitutes the course of 28 blades under the sensor (the number of blades located in I level compressor).

On the basis of analysis of portraits of the blades no. 1, 11, 3, shown in Tab. 1-3, it can be concluded that the most damaged blade is blade No. 1 (it has the majority of „+++”). Blade No. 11 is slightly damaged, and blade No. 3 is „healthy” (almost pure portrait of a blade).

Analyzing the portraits of various blades, it can be said that those obtained for the 2 MHz are consistent with those obtained for 500 kHz. This is very important, as having weaker and, above all, cheaper apparatus, it is possible to capture interesting changes to the technical condition of the blades.

4. Summary

The diagnostic model φ_{T12T01} allows to reproduce a technical condition (external – cracks and internal – overheating) of a turbomachine blade and observe the changes in subsequent periods of Θ_0, Θ_1, Θ_2, diagnosis etc.

φ_{T12T01} diagnostic model is a parametric, accurate and development model. The technical condition in a given case is mapped to the change of 11 parameters. The number of parameters can be increased by increasing the reproduction accuracy of the signals measured with corresponding correlation and spectral power density functions.

φ_{T12T01} diagnostic communicative model is presented in the form of a parametric portrait, easy to interpret during the machine operation;

The results for the φ_{T12T01} model at different sample rates (500 kHz and 2 MHz) are compatible, so even with a smaller sampling; changes of the technical condition of the blades are captured.

The portraits of blades established from φ_{T12T01} model for different sampling rates confirm the same condition.

Acknowledgement

The paper was supported by the Bialystok Technical University under the research project No. W/WM/10/2011.

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Tab. 1. Portrait of blade No. 1 for frequency 500 kHz and 2MHz

	A0	A1	A2	A3	A4	A5	B0	B1	B2	B3	B4	B5
	Model φ_{T12T01} – portrait of blade No. 1, velocity 6900 rpm, f = 500 kHz											
Cycle 1					+	+	+	+	+			
Cycle 2		+	+			+	++	++	++	++	+	++
Cycle 3		+	+			++	+++	+++	+++		+++	++
Cycle 4					+							+
Cycle 5						+	++	++	++	+	+	+
Cycle 6		+	+			+	++	++	++	++	++	+
Cycle 7					+	+				+		++
Cycle 8							++	++	+	+	+	
Cycle 9						+	++	++	+	+		+
Cycle 10							+	+	+	+	+	
Cycle 20					++	++	++	++	++	++	++	+
Cycle 30		+	+	+		++	+++	+++	+++	+	+++	++
Cycle 40							+	+	+	+	+	
Cycle 50						+	++	++	++	++	+	+
Cycle 60		+	+	+		+	++	++	++	+	+	+
Cycle 70		+	+	+		+	++	++	++	++	++	+
Cycle 80							+	+				+
Cycle 90									+	++	+	
Cycle 100						+	+	+	+	+	+	+
Cycle 200						+	++	++	+	+		++
Cycle 300						+	++	++	++	+	+	+
Cycle 400					+		+	+	+	+		+
Cycle 500		++	++	++		++	++	++	++	++	++	+++
Cycle 600		+				+	++	++	++	++	+	+
Cycle 700				+	++		++	+	+			+
Cycle 800							++	++	+	+	+	+
Cycle 900		+				+	++	++	++	++	++	+
Cycle 1000							++	++	++	++	++	
Cycle 2000					+					+		
	Model φ_{T12T01} – portrait of blade No. 1, velocity 6900 rpm, f = 2 MHz											
Cycle 1		++	++	++	++	++	++	++	++	++	+	++
Cycle 2		+	+	+	+	+	+	+	+	+	+	+
Cycle 3							+				+	
Cycle 4		+	+	+	+	+	+	+	++	++	+	+
Cycle 5		++	++	++	++	++	++	++	++	++		++
Cycle 6		+	+	+	+	+	++	++	++	++		+
Cycle 7		+	+	+	+	+	++	++	++	+		+
Cycle 8		+	+	+	+	+	+	+	++	++	++	+
Cycle 9		+	+	+	+	+	+	+	+	+	+	+
Cycle 10		++	++	++	++	++	+++	+++	+++	++	+	++
Cycle 20							+	+				
Cycle 30		+	+	+	+	+	+	+	+	++	++	+
Cycle 40		++	++	++	++	++	++	++	+	+		++
Cycle 50		++	++	++	++	++	+++	+++	+++	+++		++
Cycle 60		+	+	+	+	+	+	+	+			+
Cycle 70		++	++	++	++	++	+++	+++	+++	++		++
Cycle 80		+	+	+	+	+	+	+	++	+++	++	+
Cycle 90		+	+	+	+	+	+	++	++	++	++	+
Cycle 100		+	+	+	+	+	+	+	+	+	+	+
Cycle 200							++	++	+		+	
Cycle 300		+	+	+	+	+	++	++	++	+		+
Cycle 400		+++	+++	+++	+++	+++	+	++	++	++	+	+++
Cycle 500							+	+			+	
Cycle 600		+	+	+	+	+	++	++	++	++		+
Cycle 700							+	+	+	+		
Cycle 800		+	+	+	+	+				+		+
Cycle 900							+					
Cycle 1000												
Cycle 2000							+	+	+	+	+	

Tab. 2. Portrait of blade No. 11 for frequency 500 kHz and 2MHz

	A0	A1	A2	A3	A4	A5	B0	B1	B2	B3	B4	B5
	Model φ_{T12T01} – portrait of blade No. 11, velocity 6900 rpm, f = 500 kHz											
Cycle 1			+	+	+		+	+				
Cycle 2		+	+	+		+						+
Cycle 3					+							
Cycle 4		++	++	++	+++					+		
Cycle 5							+	+	+	+	+	
Cycle 6		++	++	++	++	+					+	+
Cycle 7		++	++	++	+	+	+++	+++	+++		+++	
Cycle 8					+		+	+	+	+	++	
Cycle 9		++	++	+		++						++
Cycle 10							+	+	+	+		
Cycle 20						+	++	++	++	++	++	
Cycle 30										++	+	
Cycle 40							+	+	+	+	+	
Cycle 50		+	+	+	++							
Cycle 60		+	+	+		+						+
Cycle 70		++	++	++	++	++					+	++
Cycle 80							+					
Cycle 90					+							
Cycle 100		+	+	+	++							
Cycle 200		+	+	+	+							
Cycle 300		+	+	+	+							
Cycle 400					+							
Cycle 500							+	+	+	+	++	
Cycle 600				+	+							
Cycle 700							+	+	++	++	++	
Cycle 800		+	+	+		++						+
Cycle 900		+	+	+	+							
Cycle 1000					+		+	+	+	+	+	
Cycle 2000		+	+	+	+					+		
	Model φ_{T12T01} – portrait of blade No. 11, velocity 6900 rpm, f = 2 MHz											
Cycle 1												
Cycle 2												
Cycle 3		+	+	+	+	+		+	+	+		+
Cycle 4												
Cycle 5												
Cycle 6		+	+	+	+	+	+	+			+	+
Cycle 7											+	
Cycle 8												
Cycle 9											+	
Cycle 10												
Cycle 20												
Cycle 30		+	+	+	+	+	+	+	+	+		+
Cycle 40							++	++	+		+	
Cycle 50												
Cycle 60												
Cycle 70												
Cycle 80		+	+	+	+	+	+	+	+		+	+
Cycle 90											+	
Cycle 100							+				+	
Cycle 200										+	+	
Cycle 300							+				+	
Cycle 400											+	
Cycle 500												
Cycle 600												
Cycle 700												
Cycle 800		+	+	+	+	+						+
Cycle 900												
Cycle 1000								+	+	+		
Cycle 2000		+	+	+	+	+	+	+	+	++		+

Tab. 3. Portrait of blade No. 3 for frequency 500 kHz and 2MHz

	A0	A1	A2	A3	A4	A5	B0	B1	B2	B3	B4	B5
	Model φ_{T12T01} – portrait of blade No. 3, velocity 6900 rpm, f = 500 kHz											
Cycle 1		+	+	+	+				+	+		
Cycle 2						+						+
Cycle 3									+	+		
Cycle 4												
Cycle 5						+						++
Cycle 6					+				+	+	+	
Cycle 7					+							
Cycle 8		+	+	+	+			+	+	+	+	
Cycle 9												
Cycle 10						+						+
Cycle 20												
Cycle 30												
Cycle 40								+	+	+	+	
Cycle 50						+						
Cycle 60												
Cycle 70						+						+
Cycle 80												
Cycle 90												
Cycle 100					+	+						
Cycle 200												
Cycle 300					+							
Cycle 400												
Cycle 500												
Cycle 600												
Cycle 700												
Cycle 800												
Cycle 900												
Cycle 1000									+	+	+	
Cycle 2000		+	+	+	+					+	+	
	Model φ_{T12T01} – portrait of blade No. 3, velocity 6900 rpm, f = 2 MHz											
Cycle 1												
Cycle 2		+	+	+	+	+	+	+	+	+		+
Cycle 3							+	+			+	
Cycle 4		+	+	+	+	+	++	+	+		+	+
Cycle 5												
Cycle 6												
Cycle 7		+	+	+	+	+	+	+	+	+	+	+
Cycle 8												
Cycle 9												
Cycle 10											+	
Cycle 20							+	+			+	
Cycle 30												
Cycle 40												
Cycle 50												
Cycle 60		+	+	+	+	+	+	+	+	+		+
Cycle 70											+	
Cycle 80							+	+			+	
Cycle 90		+	+	+	+	+	+	+	+	+		+
Cycle 100		+	+	+	+	+	+	+	+	++	+	+
Cycle 200												
Cycle 300							+				+	
Cycle 400												
Cycle 500												
Cycle 600							+				+	
Cycle 700												
Cycle 800												
Cycle 900											+	
Cycle 1000							+					
Cycle 2000		+	+	+	+	+	+	+			++	+

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