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NON-DESTRUCTIVE METHODS APPLIED TO AVIATION EQUIPMENT TESTING IN SERVICE

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Abstract

The paper describes the main non-destructive methods enabling the incipient failure detection concerning various elements of aircraft. Some kinds of failures caused by usual wear and tear in tribological systems as well as fatigue wear in turbine engines and airframes of planes and helicopters are considered. Theoretical analysis and practical verification were used to check the practiceability of various methods in wear process testing and craks detection (methods: XRF, ASO, flaw detection, vibro-acoustic). Attention was paid to necessity of taking account of the stochastic processes during calculation of probability density function for elements damage and permissible diagnostic levels.

I. Introduction

Wide range of diagnostic testing in aviation is put into practice by means of various non-destructive methods. The methods are used for cracks history finding, state of technology control and technological forecasting.

Not so long ago the term non-destructive testing was used to describe mainly methods enabling detection of cracks as well as erosive and corrosive damages. The term "non-destructive testing - NDT" should be presently used for description of the following methods: the methods enabling calculation of wear degree of tribological systems, vibro-acoustic methods and others. The group of non-destructive methods contains some methods making use of various physical phenomena for location finding and dimensions assessment of arising in operating process defects, shape changes of elements, calculating of stress distribution, physical features assessment, etc.- without operational characteristics of the element changing. The active methods and the passive ones may here be discriminated.

The active methods need application of various forms of energy (for example: electromagnetic waves, magnetic fields,etc.) as well as watching interaction with tested element (material). The passive methods are based on receiving signals coming from tested object (element).

Application of non-destructive methods in aviation is caused by need of ensuring safety of flight, need of confirmation of stability and reliability of the aircraft elements and assemblies and need of their high technical availability. Economic considerations have also an influence on NDT application in process of aircraft operation. These methods enable technical state testing of many elements without or with their partial dismantling - so, the methods may be applied at any moment, for example after landing in difficult conditions when so called "hard landing" can take place after flights in very turbulent air (when eventuality of cracks occuring may take place), after foreign objects ingestion by engines. Non-destructive testings enable detection and defects assessment as well as cracks development rate watching and further operation or regeneration (repair) need forecasting. Advantages and NDT methods potentials associated with presently possible computerization of calculation and prolonged operating information storage enable aircraft operation not only according to statistic overhaul life but also according to aircraft technical state.

II. Significance of non-destructive testing in diagnostic processes

Diagnostic processes are carried out within diagnostic systems, which include:
- methods
- diagnostic devices
- technologies and alghoritms of causes (history) finding process, state inspection and prognosis.

Relations between these elements of a diagnostic system constitute the whys and wherefores unions: defined state inspection method (including for example non-destructive test method) implies the use of defined diagnostic device which functions according to physical phenomena pertinent to this method and application of elaborated (and employed) diagnostic levels of values and physical measures resulting exactly from the accepted method as the only one feasible for use or the optimal one due to the time of inspection, costs, etc.

Methods in diagnostic system:
- state inspection (control)
- allocation of diagnostic levels
- diagnosis development
- prognosis development .

Diagnostic devices:
- non-automated
- semi-automated
- automated.

Technologies and alghoritms:
- state inspection by the use of diagnostic device
- formation of a diagnosis on the ground of diagnostic levels values
- prognosis for further operation.

Diagnostic system of an airship should comprise the following: kinds and causes of inefficiencies, physical processes causing inefficiencies, character of inefficiencies and possible effects caused by an element failure, etc.

Diagnostic system is created at the stage of exploitation system design while an airship is developed. This system is constantly updated and improved in process of its use (application). New methods, devices and technologies of inspection are introduced into it as a result of constant analysis of technical inefficiencies observed (occured). Inefficiencies which led to break-downs and aviation disasters are the particular case of such ones. Steps of diagnostic system creation and improvement are presented in Fig.1.

Worth mentioning is that diagnosing of elements and assemblies is the result of a wilful, anticipated "a priori" or demanded reliability state of introduced diagnostic lists of elements, lists compiled as a result of exploitation experience(1,2).

There are no universal diagnostic methods including non-destructive testing ones as well. There is a multitude of them. It is difficult to classify such methods. Fig.2(10) presents a trial of classification in form of three columns containing static, dynamic and mixed methods (taken as an example). Some features and characteristics of physical processes which make the accomplishment of diagnostic task feasible have been employed in it.

Main methods of non-destructive testing used for detection and quantitative evaluation of wear products of tribological nodes and for detection of elements defects are arranged in Table 1 and 2.(3)

III. Testing methods of tribological systems wear in aviation turbin engines and break-down state detecting

The main assemblies in turbine engine which are subjected to wear and tear in tribological process are fuel pumps and bearing systems. Diagnosis of fuel pumps is carried out with the use of vibro-acoustic methods. Diagnosis of bearing system elements is carried out by analysis methods of wear products collected in oil system. There are three basic methods of wear products analysis: radioisotope X-ray fluorescence method (XRF), spectral analysis me-

thod (ASO) and ferromagnetic method (F): each of them has its advantage. XRF method enables finding the concentration of main elements, such as Fe, Cu, Pb of any granulation. ASO method enables testing a dozen or so of chemical elements but its main feature is relatively high error for broad range of wear products particles size.
F method enables testing of ferromagnetic elements, mainly Fe and definition of wear products quantity.

Concentration of wear products (ppm or g T) in tested oil sample is described by the equation :

$$C(t)=f(\tau)\cdot S\cdot Q(t)\cdot \frac{V}{v}\cdot \frac{1}{M_0} \qquad (1)$$

where: $f(\tau)$ - normalized function of wear products sedimentation in an oil system after time τ from the moment of engine shutdown: (see Fig.3):
S - coefficient of wear products dispersion in an oil system (obtained experimentally):
Q - total mass of wear products g :
V - oil volume in an oil system:
v - volume of oil sample tested:
M_o- mass of oil.

In course of aero-engine exploitation process oil consumption changes relatively little. It may be accepted, that values S, V, v, M_o are subjected to little changes. If the moment of oil sample taking is assumed constant (τ = const.) then the equation C(t) describes properly changes of wear products quantity in function of engine useful life-time.

Typical flow of C(t), i.e. changes of wear products concentration in type R-13 turbine engine is presented in Fig.4 (XRF method)(4). The beginning of enhanced wear took place after 150 hrs of operation. The engine was withdrawn from operation. Figure shows XRF spectrum which intensity equivalent to the surface below $K_{\alpha Fe}$ peak is proportional to C_{Fe} in oil sample tested. While engine dismantling it was found that one of the packing rings of the high pressure turbin roll bearing was worn (see Fig.5).

Fig.6 presents an interesting case of break down wear of one of the packing rings (first maximum) and the beginning of one of the bearings wear (second maximum). An example of technical analysis of worn out bearing is shown in Fig.7. Worth mentioning is laser interferometry application in order to find the depth of pinholes on the bearing track.

Systematic study of wear processes of aviation turbin engine bearing systems in course of operation enables the evaluation of break down wear development time distribution t_a - from the moment of detection to the moment of withdrawal from operation (see Fig.8). These observations are helpful to evaluate the frequency of oil samples taking.

Figures 9 and 10 illustrate examples of spectral method (ASO) application to detect break down state of aviation piston engine. Testing was performed with the use of FAS-2 device(9). Good indicators of imminent break down state for this type of engines are concentration ratios of different chemical elements. For example: $p = C_{Fe}/C_{Cu}$, $q = C_{Fe}/C_{Al}$, etc. Similiar works are, among others, performed by Thomas and Howard(5).

Process of wear products concentration change of a defined chemical element C(t) is a random process and its values (realizations) are analog random variables C_j, j = 1,2,...(see Fig.11). Therefore, the random variable C_j distribution is the full range probabilistic characteristic of a normal engine operation. This distribution may be described by a distribution function $F(C_j)$ of the variable C_j or by a probability density function $f(C_j)$ of the same variable.

Interval estimation E(C) for time intervals $t_i - t_{i+1}$ (i = 1,2,...) and standard σ deviation enable computation (evaluation) of P_i interval values.

$$P\{C_{iD} \leqslant C \leqslant C_{iG}\} = P\{y_{iD} \leqslant \frac{C-E(C)}{\sigma} \leqslant y_{iG}\} \quad (2)$$

$$y_{iD} = \frac{C_{iD}-E(C)}{\sigma} \; ; \; y_{iG} = \frac{C_{iG}-E(C)}{\sigma} \quad (3)$$

$$E(C) = \bar{c} \quad (4)$$

Precise examination of abrasive wear changes of aero-engine tribological systems assumed to constitute a stochastic process, is the way to exploit substantial potentialities for prolonging engine overhaul life. The analysis is based on measurements of metal elements concentration in wear products.

IV. Flaw-detection methods of fault finding in engine and airframe structural elements.

Flaw-detection methods used in course of air-ships operation are distinguishable by their specific character. There is no doubt that the following features deserve mentioning. The methods find application:

- in nodes of difficult accessibility,
- in field conditions,
- when structural elements are covered with various protective layers.

The flaw-detection methods fullfil the requirement of high-rate and reliable detectability of corrosion and fatigue cracks. The use of these methods in course of operation may be either forecasted by manufacturer or may result from a set of information on structural element behaviour during operation.

It is obvious that not each of the detected failures is of critical character. It is however of great importance to fix criteria for recognition of some defects as inadmissible and for frequency of inspections.

Wear and surface or volumetric cracking (z) of structural elements are often initiated by pulse loadings of stochastic distribution which make the discussed problem being so complex. Therefore, probability density function U (t,z) should be determined for each case separately, from the equation(6):

$$\frac{\partial U(t,z)}{\partial t} = -k\,U(t,z) - b\,\frac{\partial U(t,z)}{\partial z} + \frac{1}{2}a\frac{\partial^2 U(t,z)}{\partial z^2}, \quad (5)$$

where: $k = \lambda P$

$b = \lambda(1 - P)P_1 h + 2\lambda(1 - P)P_2 h$

$a = \lambda(1 - P)P_1 h^2 + 4\lambda(1 - P)P_2 h^2$

λ - occurance rate of load pulses causing (inducing) structural element wear:

P - probability of an element wear:

P_1 - probability of an element efficiency in t moment:

P_2 - probability of an event when an element is of greater than limited wear but still not damaged at t moment:

h - an increment, quantized magnitude of a propagating crack, wear, etc.:

z - analysed parameter.

If parameters are of constant values, the solution of the equation (5) may often be written in form of:

$$U(t,z) = \frac{1}{\sqrt{2\pi a t}}\, e^{-\frac{(z-bt)^2}{2at} - kt} \quad (6)$$

V. Vibro-acoustic testing methods of engine and airframe structural elements technical condition

Technological condition monitoring of structural elements subjected to wear processes in open systems or being damaged in effect of cracking, etc. is in many cases possible when using modern, vibro-acoustic methods. In terms of measuring potentialities these methods are already well developed. Suitable measuring sets have already been put into service. There are numerous methods (computer-aided) of vibro-acoustic signal processing, i.e. processing either signals of mechanical vibration measured on element assembly housings or acoustic signal being a secondary effect of vibration.

The vibro-acoustic methods enable (as many experiments have shown) very precise detection of pre-failure conditions arising in course of operation and leading, sooner or later, to catastrophic conditions endangering flight safety.

The basic problem to be practically solved is the question of selecting the most optimal measurement technique, and among others:

- the choice of vibration sensor location,
- vibration spectrum processing,
- diagnostic levels estimation.(7)

Two very intersting examples of vibro-acoustic methods application to detect airship inefficiencies will be presented below.(8)

Acoustic measurements enabled detection of inefficient turbine engine and air-intake body sealings. The comparison of noise spectra at the engine air-intake for different distances from an aircraft (L_m/L_s , L_s - an aircraft lenght) and for various aircrafts has revealed untypical frequency f = 350 Hz (see Fig.12). Sound intensity level change for the value f_{350} in function of a distance from the air-intake has clearly shown the location of the sound source: it appear that deflection of a part of the aircraft skin caused by rivets damage was the sound source.

The blade antenna of a helicopter is provided with a textolite insulating layer. The antenna is fixed to the helicopter construction with bolts. The change of resonant vibration frequency may be expressed by the following equation:

$$f_p = \sqrt{\frac{J_p}{J}}\, f , \qquad (7)$$

where: f_p - resonant frequency of an antenna with a crack,
f - resonant frequency of an antenna without any failure,
J, J_p - moments of inertia of cross sections of an undamaged and damaged antennae.

Natural vibration frequency measurements may be very helpful in detecting antennae damages comprising cracks of an insulation layer or of fastening bolts. Fig.13 illustrates values of f for helicopter antennae in operational use.

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Table 1.

METHODS USED IN WEAR PRODUCTS FINDING AND TESTING

Method name	Range of application	Method features	Remarks
Wear products collecting in filters and centrifuges	all particles	1) discrete and qualitative read - out 2) experience needed for interpretation	method in common use
Magnetic plugs and magnetic particles detectors	large particles	1) discrete and qualitative read - out 2) lack of data about non-magnetic wear products	good resuls in case of failures caused by scuffing and seizing
Ferrography	all magnetic particles	1) quantitative read - out 2) lack of data about non-magnetic wear products	very expensive equipment ; methods of the future
Spectroscope analysis methods (spectral, radiographic, isotopic)	small particles	1) laboratory read - out 2) possibility of quantitative and qualitative analysis	applicable to detection of state of failure and prognosis
Automatic counters of particles	all particles	1) heavy influence of other solid particles	applicable to monitoring of hydraulic systems
Vibro- acoustic and acoustic emission	surface state	1) difficult interpretation of data due to high noise level background	possibility of automatization

Table 2.

MAIN METHODS AND TECHNIQUES OF NON - DESTRUCTIVE TESTINGS

METHOD	TECHNIQUE	Kinds of materials tested		Kinds of defects detected		
		Ferro - magnetics	Non magnetics	Surface	Subsurface	Inertial
OPTIC	naked eye magnifying glass endoscope	+	+	+	–	–
PENETRATION	coloured fluorescence	+	+	+	–	–
MAGNETIC POWDER	wet dry	+	–	+	+	–
ULTRASONIC	echo (pulses) transmission (shadow)	+	+	+	+	+
EDDY CURRENT	current carrying touching coil passage coil	+	–	+	+	–
RADIOLOGICAL	x-ray radiography gammagraphy	+	+	+	+	+

NOTE : + denotes feasibility of control and defect detection
– denotes method unsuitability

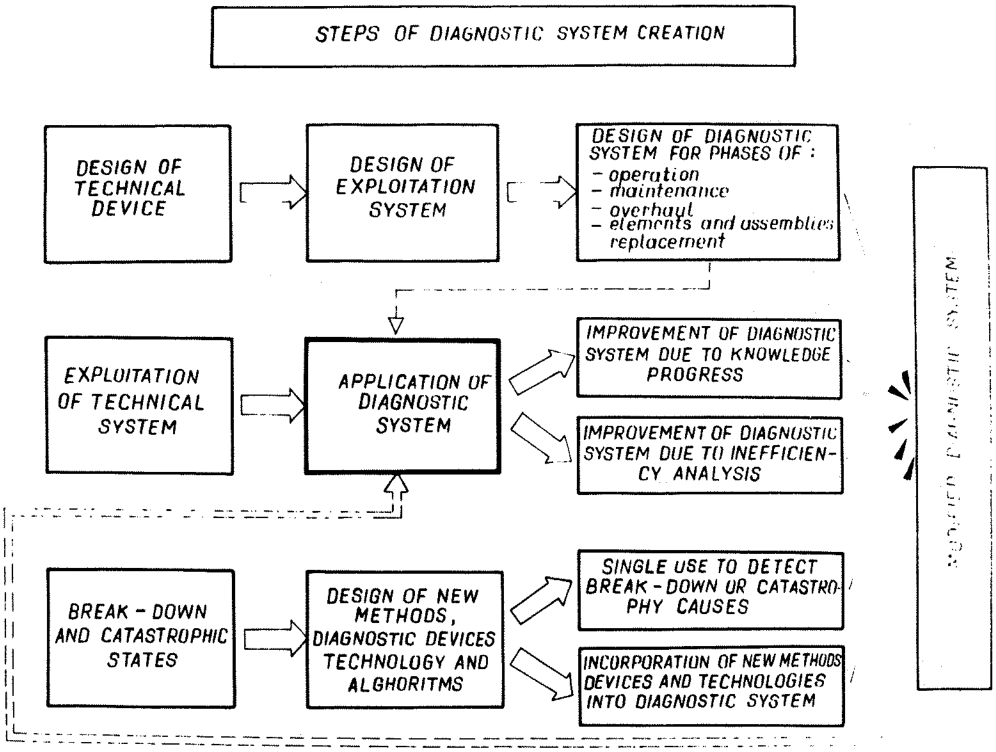


Figure 1. Steps of diagnostic system creation

DIAGNOSTIC METHODS

	STATIC	DYNAMIC	MIXED
Parametrs and values measured (examples)	Changes of geometric values Wear products concentration Clearance change Head-lights setting Stearing knuckle clearances	Vibration characteristics Acoustic charakteristics Characteristics of transition processes Surface temperature changes	Routine measurement of wear products concentration Routine measurement of fumes composition etc...
	During measurement technical device is inoperative	During measurement technical device is operative	

Figure 2. Diagnostic methods

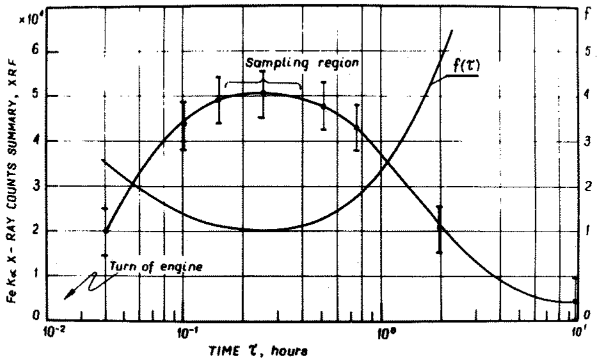


Figure 3. Sedimentation curve Fe and f ( ) for abraded matter contained in turbine engine oil installation

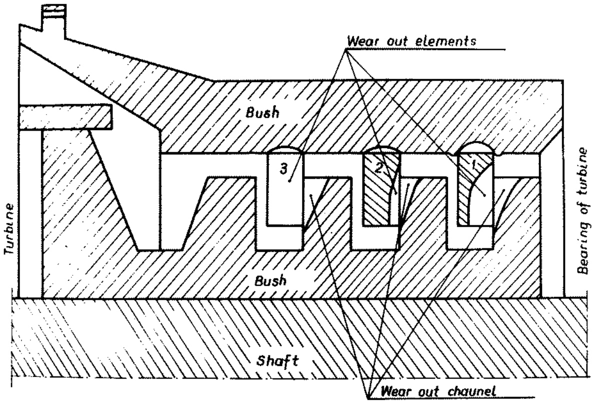


Figure 5. Longitudal section of the damaged packing ring of high pressure turbine roll bearing.

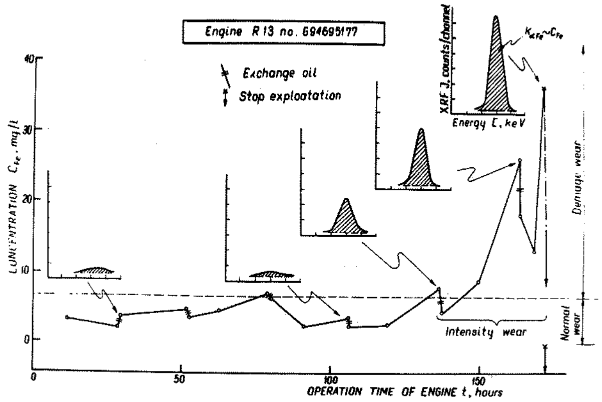


Figure 4. Iron concentration change C_{Fe} in a turbine engine with break-down failure of packing rings.

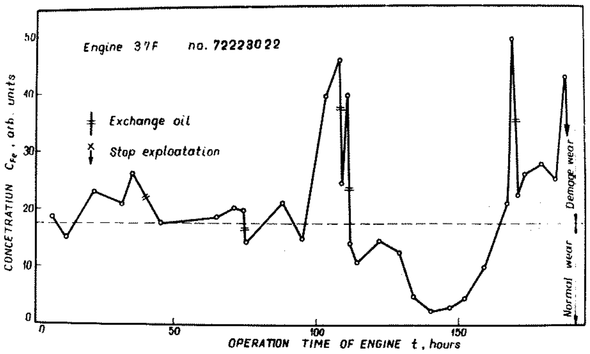
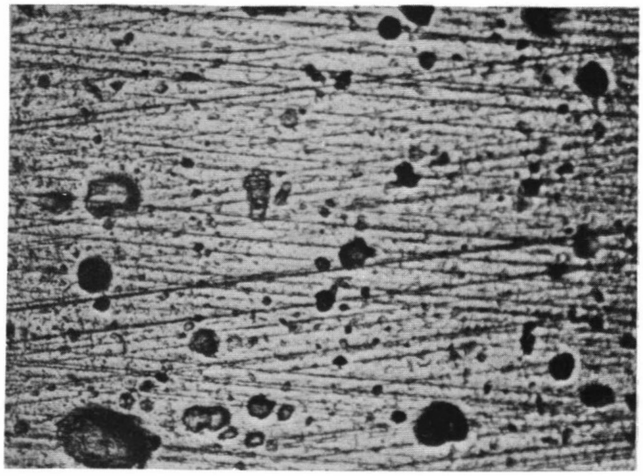


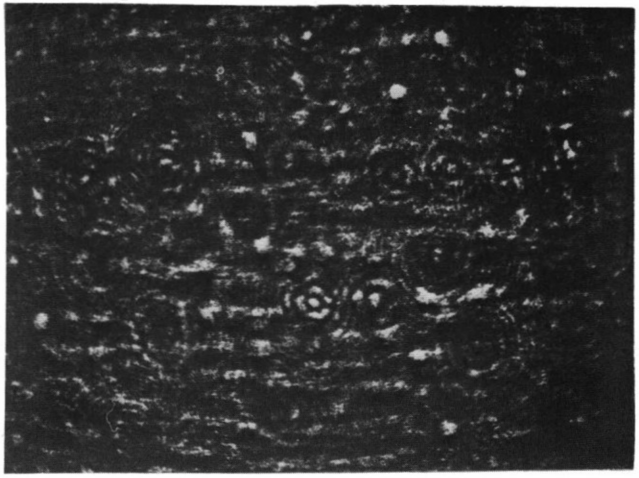
Figure 6. Iron concentration change C_{Fe} in a turbine engine with break-down wear of packing ring and bearing.

Figure 7. Surface damage of the engine bearing track (x50):

(a) track after full life-time operation



(b) pits and breaches after 150 hrs of operation



(c) holographic picture of a damaged track (interference rings are seen)

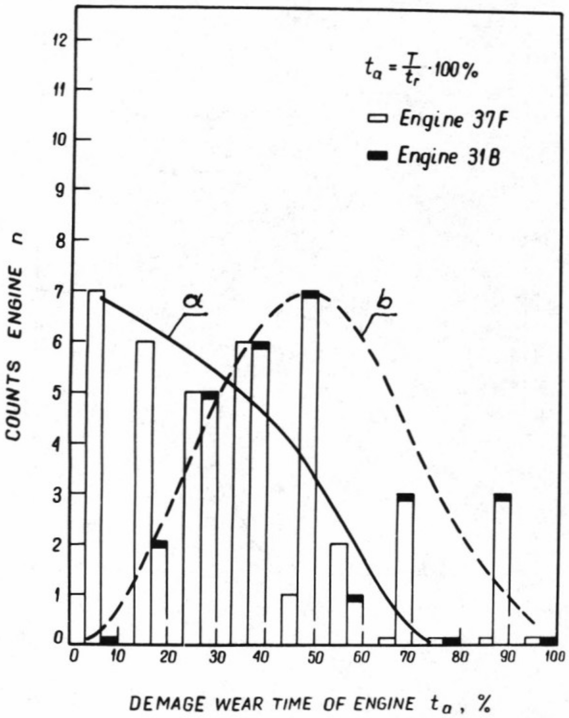


Figure 8. Histograms of break-down wear development times of bearing system; (a) two spool aero-engine, (b) one spool aero-engine.

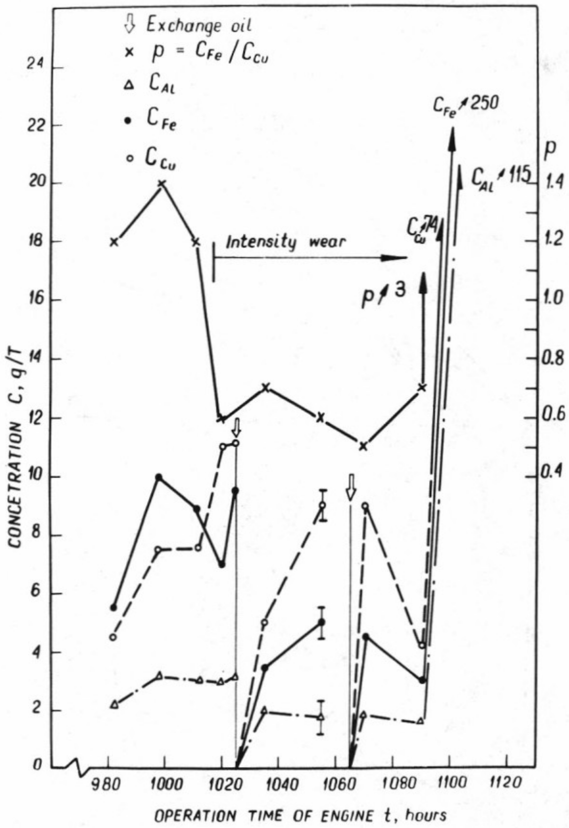


Figure 9. Wear products concentration change in an piston aero-engine before bearing bush seizing

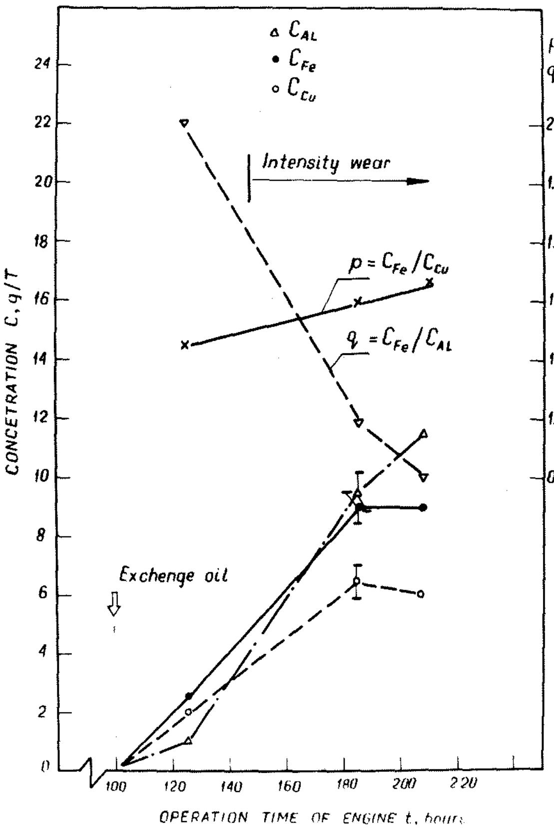


Figure 10. Wear products concentration change in aero-engine before a piston seizing.

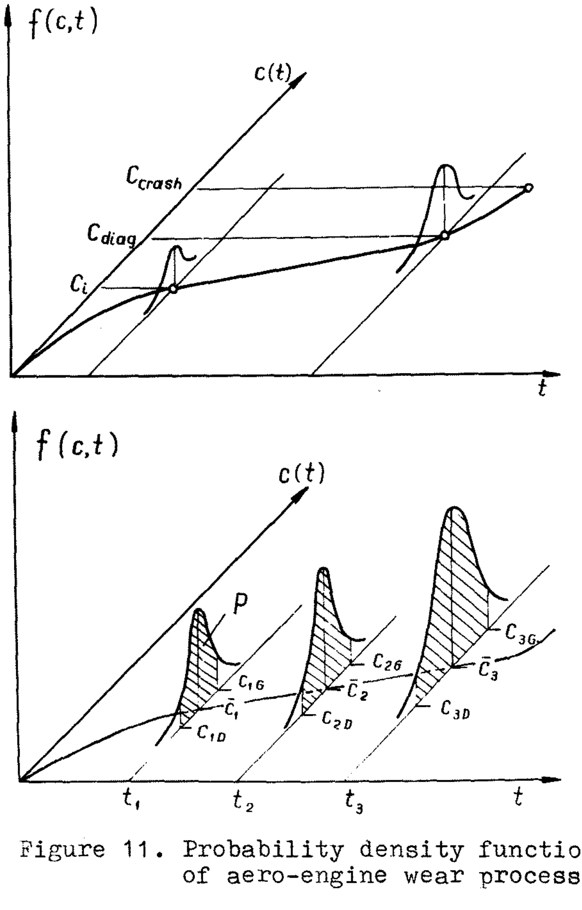


Figure 11. Probability density function of aero-engine wear process

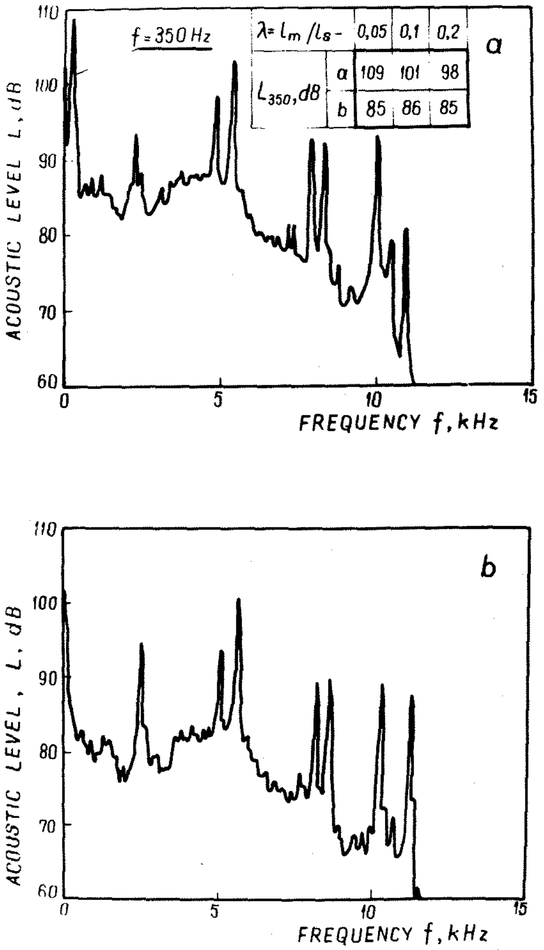


Figure 12. Acoustic spectrum of engine noise in front of an aircraft

(a) inefficient engine and air-intake body sealings

(b) efficient engine and air-intake body sealings

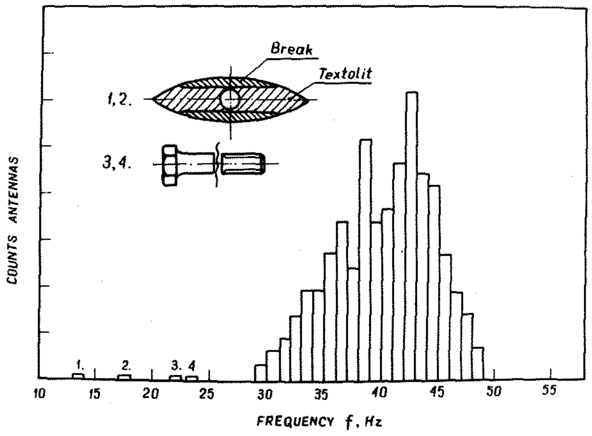


Figure 13. Probability density function g(f) of antennae resonant frequencies.