TWENTY FIRST EUROPEAN ROTORCRAFT FORUM

Paper No IV.1

# DAMAGE PROPAGATION IN GEAR BOXES.

# TESTS MANAGEMENT

BY

B.Farnault, G.Genoux, E.Greco, Ch.Hebert

EUROCOPTER FRANCE

August 30 - September 1, 1995
SAINT - PETERSBURG, RUSSIA

Paper nr.: IV.1

Damage Propagation on Gear Boxes. Tests Management.

**B. Farnault; G. Genoux; E. Greco; Ch. Hebert**

**TWENTY FIRST EUROPEAN ROTORCRAFT FORUM**
August 30 - September 1, 1995 Saint-Petersburg, Russia

# 1. PROGRAMME PRESENTATION

## 1.1 Introduction

The June 1984 report of the Helicopter Airworthiness Review Panel (HARP) recommended that the UK Civil Aviation Authority (CAA) set up a working party to investigate new or improved health monitoring devices and systems..

As a result of this report, the CAA, the United Kingdom Offshore Operators Association (UKOOA) and the UK Department of transport made funds available for research and further promotion of Helicopter Health monitoring. A part of the research programme was intended to develop an helicopter transmission defects data base as well as to assess the state-of-the-art in the field of vibration analysis.

EUROCOPTER took part in this programme. Their participation was a study of crack propagation and related vibration analysis in Gearboxes. The rationale herebelow.described gives the main issues of the programme.

**-selection of representative defects:**

The selection was made by the U.K. CAA & EUROCOPTER. It was decided to focus on the main gear box and, for this contract, on gears and shafts only. Then, 8 potential defects were selected in the SUPER PUMA Main Gear Box (MGB)

**-computing and seeding defects:**

The computations necessary to choose the length and shape of the initial notch were undertaken by EUROCOPTER (ECF) with the intention to initiate and propagate a crack from this notch. This work is described in the paper.

-propagation on a Main Gear Box test bench:

EUROCOPTER's MGB test bench was used to initiate and propagate cracks from initial notches seeded by a sub contracting company.. The power spectrum profile for initiation and propagation is determined together with the initial notch length.

**-vibration analysis:**

A vibration analysis was undertaken during propagation with two objectives:

Firstly to ensure bench safety, and secondly to participate to the assessmentt of the state-of-the-art in the field of vibration analysis.EUROCOPTER vibration analysis technology was used.

**-crack propagation and vibration indicator correlation:**
Crack propagation was analysed after bench trials and a correlation was made with the indicator behavior, to assess tha ability of vibration analysis to detect crack growth.

**-programme synthesis**: CAA & EUROCOPTER will synthesize the programme once it is finished.

### 1.2 Scope

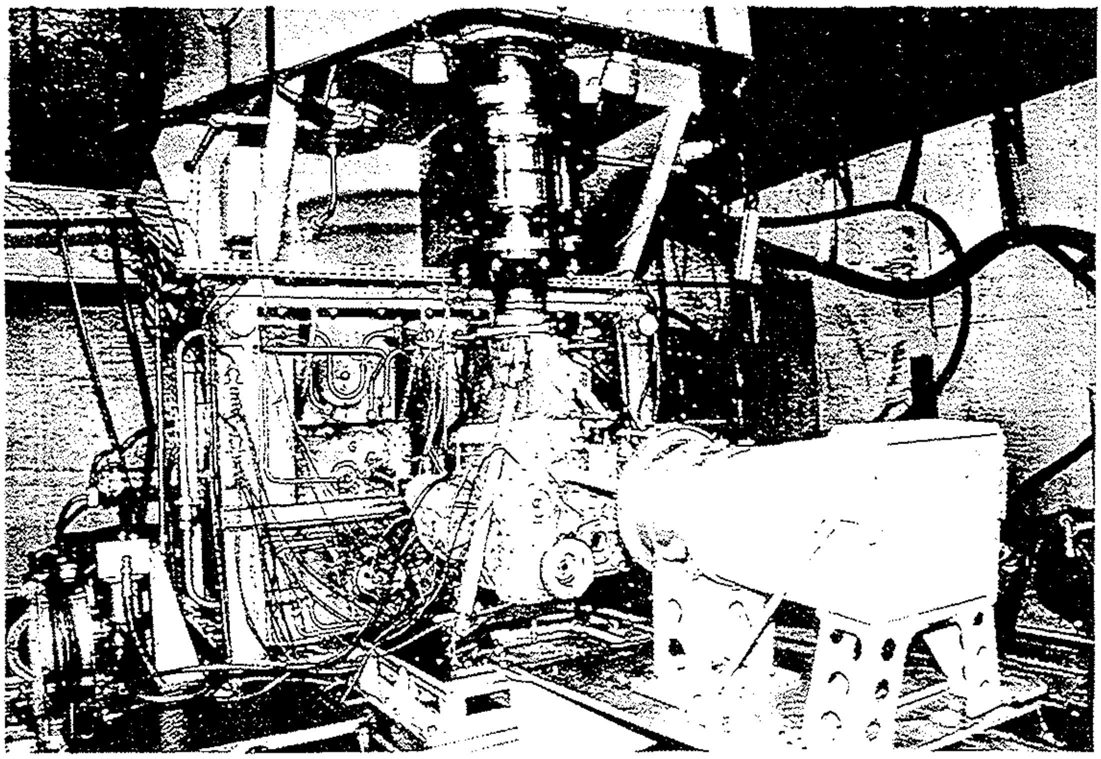
To date, the programme operations are not yet complete. This paper is thus more oriented towards the used methodology, and more precisely towards the trials management. In a first time, the constraints to be applied for conducting the test are set up. These constraints impact on initial notch computation (§2.2) and propagation monitoring by vibration analysis (§2.3). First results on these two topics are presented below.

## 2. PROGRAMME DESCRIPTION

### 2.1 Choice of defect type.

The defects have been selected according to in-service experience, incident or accident for all equivalent designs known to EUROCOPTER. In addition, the FMECA (Failure mode Effect and Criticality Analysis) of the SUPER PUMA has naturally been used.

The defects selected are Main Gear Boxes cracks only, such as tooth, shaft or web cracks. Eight different defects distributed over the whole SUPER PUMA Main Gear Box were selected.



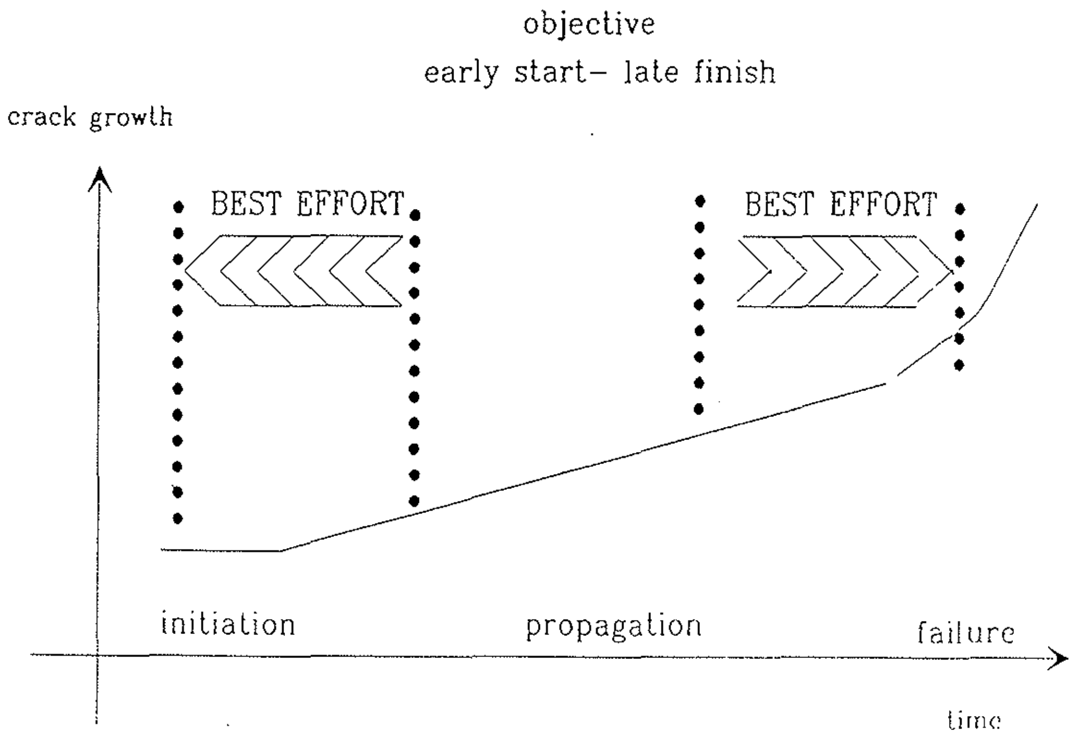
MGB TEST BENCH AT EUROCOPTER

## 2.2 Management of the trials.

As already stated, the defect data base must be used to assess the vibration analysis state-of-the-art. Thus, the ideal situation is to get a as long as possible propagation for one given defect.

In addition, on one hand, the discontinuity in the vibration signature between a healthy gearbox, and the beginning of propagation has to be minimised. This is obtained by a precise computation of the initial notch from which the crack will initiate.

On the other hand for the most critical failures, it has to be ensured that the trial will be stopped before the failure may have an impact on the bench safety. The most reliable way as it has been shown by the first trials is the vibration analysis monitoring. Indeed, the other classical means like silver meshing, or others, have never been really able to give a reliable result for this programme.



## 2.3 Initial defect computation

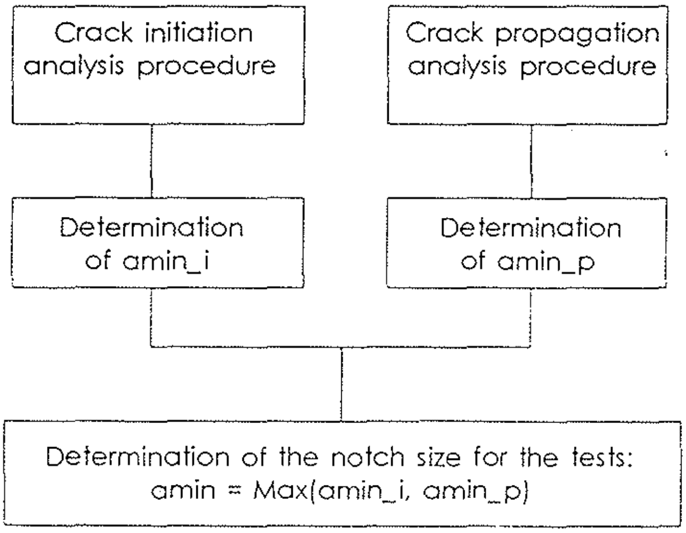
The objective of initial defect computation is to ensure that a crack can be initiated and propagated. Thus the initial notch computation is based upon the initiation constraints and the propagation constraints.

Indeed, it is physically possible for a given notch length value to initiate a crack at the notch tip but without propagation after initiation (crack arrest under nominal stresses).

It is necessary for this reason to consider limiting factors as regards both initiation and propagation.

The minimum notch length necessary to obtain both crack initiation and propagation is called a_min, for a given defect type.

The global procedure used to determine the minimum length of the notch is therefore as follows:




Where :

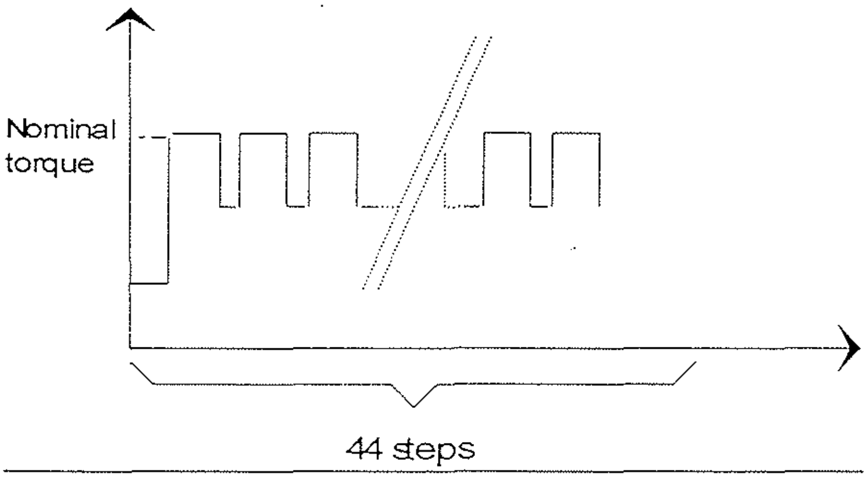
(amin_i) is the minimum notch length value to obtain crack initiation. (amin_p) is the minimum crack length value to obtain crack propagation.

The initial defect computation is made once the following assumptions have been made:

•*Input power:* The results of the programme must be used for HUMS™* validation. It is then important to be as close as possible of the actual use conditions of a HUMS ™*, i.e. nominal input power on the gear box. Thus the nominal input power level of Super Puma is used for the trials and the initial notch computations.

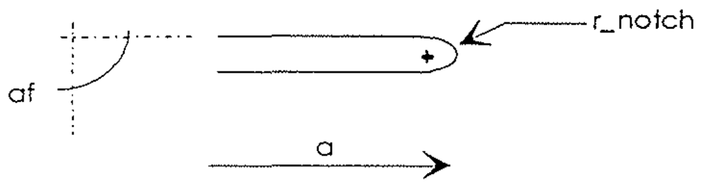
The power spectrum is defined to ensure that the crack initiates and propagates but also to identify the crack propagation time. The aplied power spectrum is divided into steps including a low level step and a higher level step. This spectrum produces "beach marks" on the fracture topography that will allow drawing a propagation curve versus bench time.

**Example of power spectrum for bench tests**




•*Crack initiation:* The initiation could be performed on a specific initiation bench, removed from the gear box, and then the propagation of the crack being performed inside the gearbox To be as close as possible of the actual HUMS ™* algorithms use, it has been decided to initiate and propagate inside the gearbox. Intiation conditions computation will then be computed with the nominal torque input level.

•*Initial notch radius* (r_notch) A notch is defined by three parameters, its length (a), the angle (af) and the notch radius (r_notch):




For most cases (af) value is obvious, and does not need calculation.. Indeed, the determination of (af) by calculation was only done for one defect.

The r_notch value is fundamental for the crack initiation. The more r_notch is small the more crack initiation is sure. But for propagation, the r_notch has no effect. A fixed value of r_notch has been chosen with the ECF subcontractor.

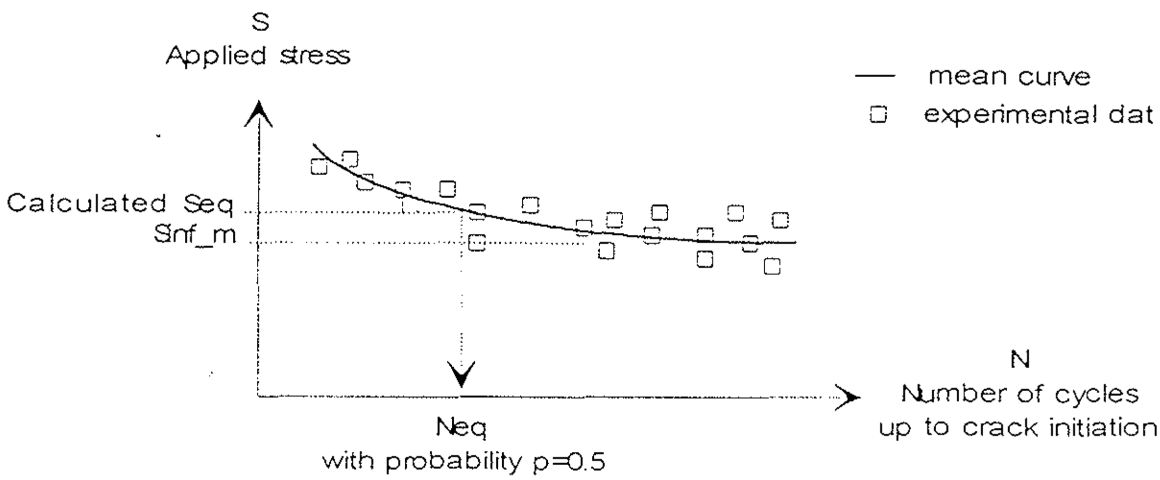
Thus the main parameter to be determined is the length of the initial notch

### 2.3.1 Minimum notch size value to obtain crack initiation

**•Limiting factor for crack initiation**

(a_min_i) represents the limitation factor applied to the length of the initial notch to ensure the initiation of the crack.

The crack initiation phenomenon is described with the Wöhler curve as follows:



S is the dynamic stress applied without static stress (Sstat) or stress concentration (kt) due to notch radius.

Sinf_m is the mean fatigue threshold of the material without kt or Sstat effects.

Seq is the equivalent S stress to be compared with Sinf_m; it takes into account the effects of :

- kt, the stress concentration factor due to the shape of the part and its notch
- Sstat, the static stress.

Then, the limiting factor for crack initiation is : LF_i = Seq / Sinf_m

Where : LF_i > 1 high probability of crack initiation

LF_i = 1 medium probability of crack initiation

LF_i < 1 low probability of crack initiation

In our study devoted to "steels without fretting corrosion" and in the vibratory regime i.e. $N>10^5$cycles, the Wöhler curve is expressed as follows:

S / Sinf_m = 1 + 0.0323 / N (N in Mcycles)

- Procedure to determine amin_i

A safety margin (sm_i) is used for initiation calculations to avoid uncertainties.

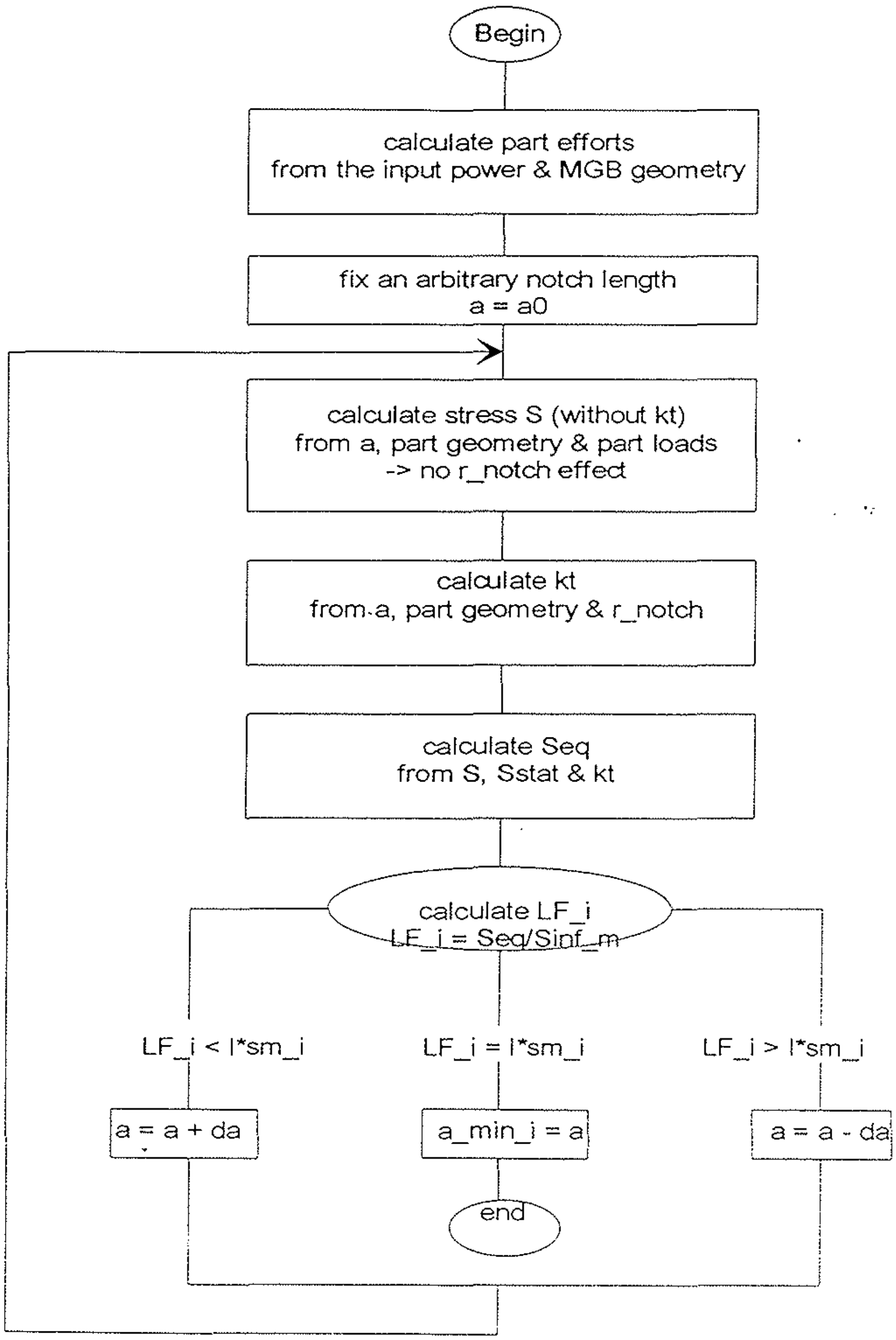
The sm_i value depends on :

-the accuracy of the calculation methods used

-the natural dispersion of the materials around the mean value Sinf_m.

We used : 1.2 < sm_i < 1.4

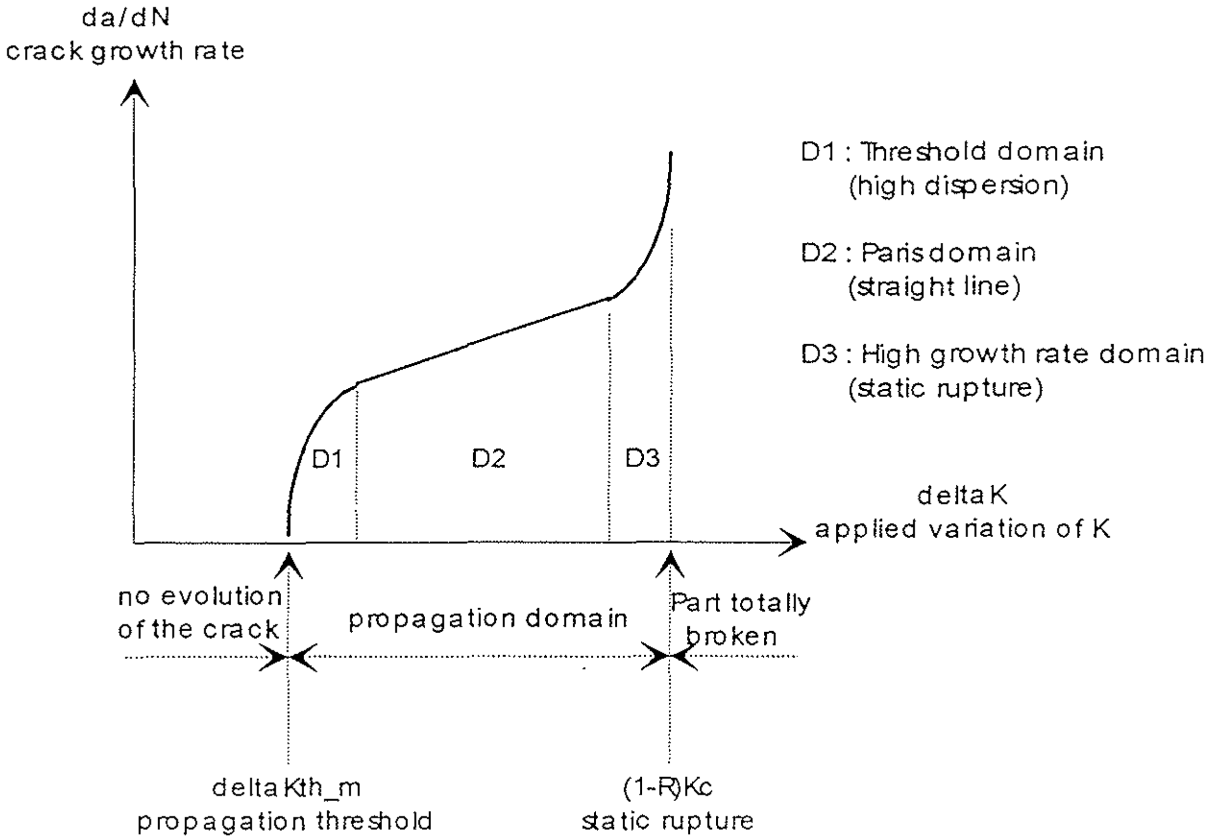
The procedure to determine amin_i is depicted below :


Begin
calculate part efforts
from the input power & MGB geometry
fix an arbitrary notch length
a = a0
calculate stress S (without kt)
from a, part geometry & part loads
-> no r_notch effect
calculate kt
from a, part geometry & r_notch
calculate Seq
from S, Sstat & kt
calculate LF_i
LF_i = Seq/Sinf_m
LF_i < l*sm_i
LF_i = l*sm_i
LF_i > l*sm_i
a = a + da
a_min_i = a
a = a - da
end

### 2.3.2 Minimum notch size value to obtain crack propagation

- **Limiting crack propagation factor**

The crack propagation phenomenon is described with the well known da/dN vs $\Delta K$ curve summarized as follows:




Where K, the stress intensity factor (SIF), is the basic parameter to fix the crack nocivity (depending on the geometry of the part and cracks as well as stresses).

Then the limiting factor for crack propagation is : $LF\_p = \Delta K / \Delta Kth\_m$

With : $LF\_p > 1$ high probability of crack propagation

$LF\_p = 1$ medium probability of crack propagation

$LF\_p < 1$ low probability of crack propagation

- **Procedure to determine amin_p**

A safety margin is used in propagation calculations (sm_p) to avoid uncertainties

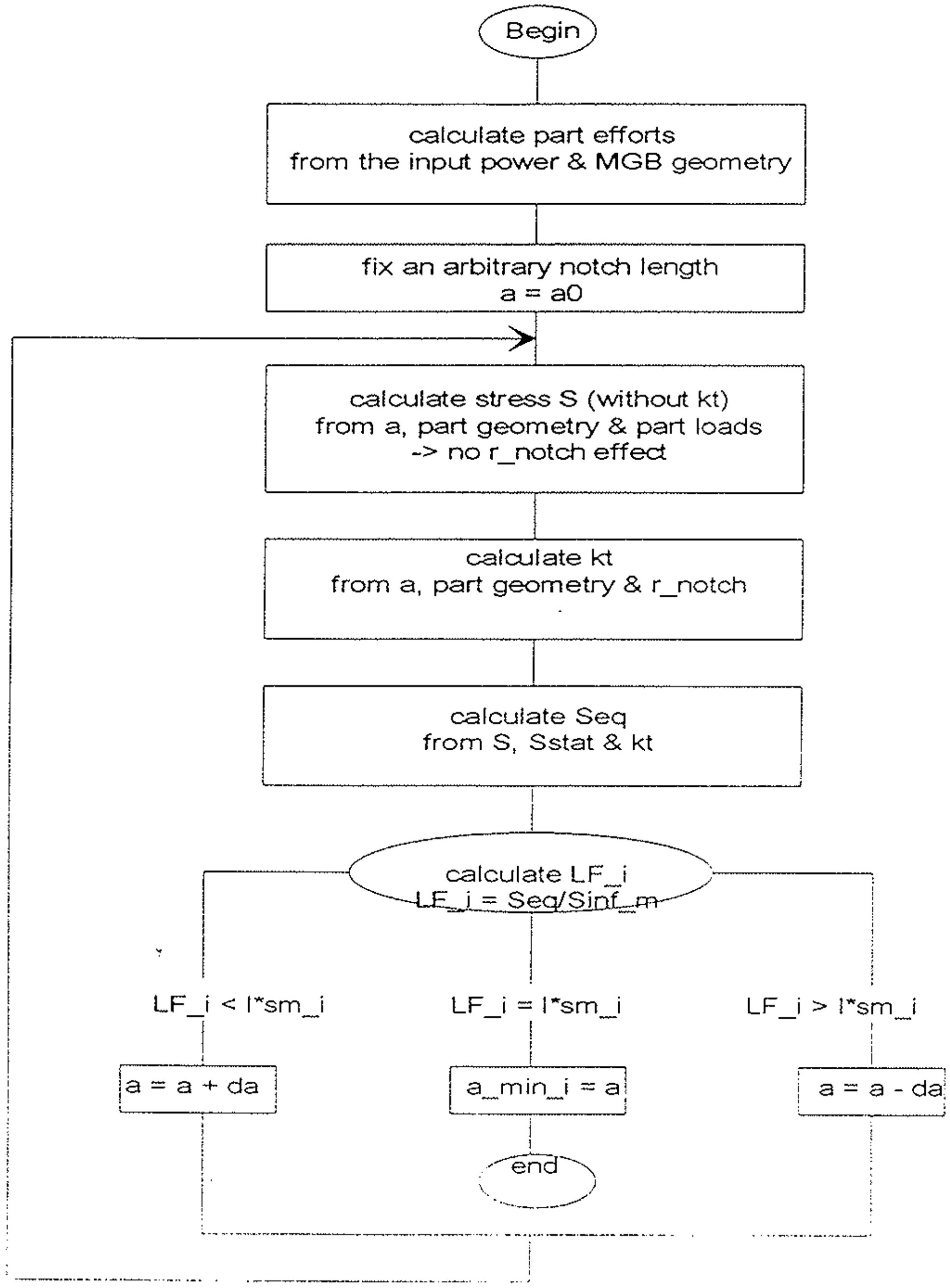
The sm_p value depends on :

- the accuracy of calculation methods applied

- the natural dispersion of the material around the mean value deltaKth_m.

We used : 1.1 < sm_p < 1.3

It has to be noted that the r_notch has no effect on amin_p determination.

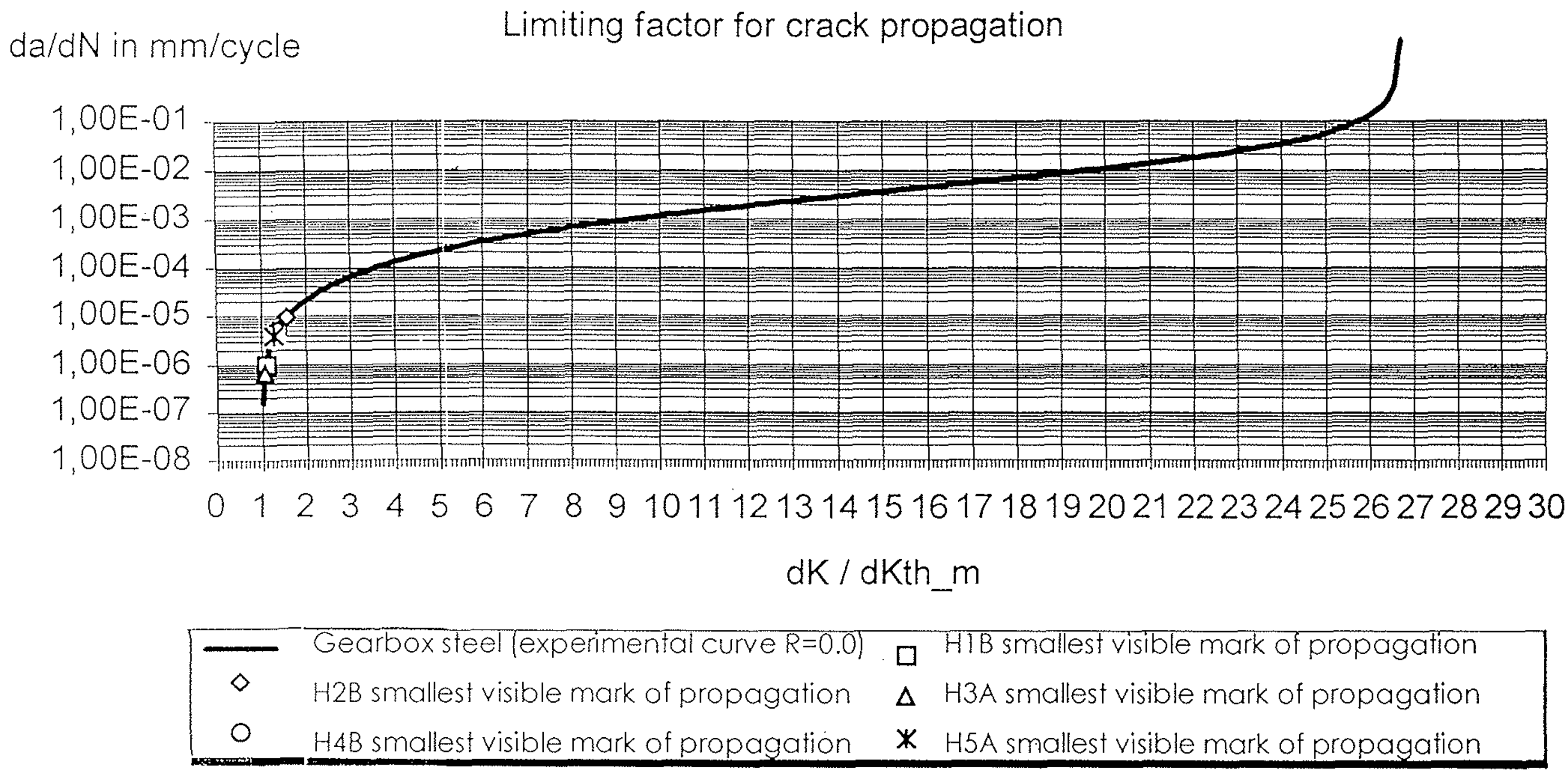


## 2.4 Practical results: actual propagation starting point

Once propagation has been completed, the part under test is removed from the Gearbox, and analysed in EUROCOPTER metallurgical laboratory. The beach marks produced by the power spectrum are analysed, and the curve illustrating the actual propagation rate versus bench time is plotted.

Up till now, the order of magnitude of the theoretical results have always been properly estimated.

On the following drawing, have been plotted five propagation starting points showing that the trials have began close to the possible propagation area, in the D1 domain referenced in the figure of § 2.3.2. This validates the model used for crack initiation and propagation. From that standpoint, the programme requirements are fulfilled.


Limiting factor for crack propagation
da/dN in mm/cycle
1,00E-01
1,00E-02
1,00E-03
1,00E-04
1,00E-05
1,00E-06
1,00E-07
1,00E-08
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
dK / dKth_m
Gearbox steel (experimental curve R=0.0)
H1B smallest visible mark of propagation
H2B smallest visible mark of propagation
H3A smallest visible mark of propagation
H4B smallest visible mark of propagation
H5A smallest visible mark of propagation

## 2.5 Vibration analysis monitoring

### 2.5.1 Introduction to vibration analysis

Vibration analysis must be defined to be able to monitor the following potential defects: Kinematic defects due to machining problems, wear, pitting (scaling), tooth damage, tooth crack, hub crack, web crack or shaft crack.

To obtain a vibration signature for these defects, the analysis needs to be synchronized with the gear or shaft rotation.

In the Super Puma MGB the rotation speeds are ranging from 265 rpm (output stage) to 23000 rpm (input stage). Synchronisation must proceed throughout this range for each gear or shaft and is to be followed by an averaging process to cancel the gear vibrations where there is no synchronisation.

The acquisition, synchronisation and averaging techniques are essential if the accuracy necessary for vibration analysis is to be obtained, but these are beyond the scope of this paper.

A set of indicators, well known in the vibration analysis world, are used to monitor the defects listed above; these are:

**Energetic indicators**

**RMS**: Root mean square, providing the energy contained in a signal. The energy of the signal increases whenever a defect occurs. This indicator activates an alarm for kinematic defects (wear, pitting, scaling) without actually locating those defects. It is usually not an early indicator and is sometimes used to confirm other diagnostics.

**Fourier transform:**

> $n\Omega$ (Fourier transform tones) these indicators are characteristics of geometric phenomena e.g. meshing frequency and others.
>
> $1\Omega$ is an indicator of a shaft imbalance
>
> $2\Omega$ is an indicator of a shaft flexion caused, for example, by a misalignement of the shaft bearings or a crack in the shaft.
>
> $m\Omega$ when m is the number of gear teeth giving an indication upon gear meshing

**Pattern indicators**

**Kr:** Kurtosis

The Kurtosis indicator allows extracting from the signal some information on impacts generated by a generalised defect of the gear teeth, hub crack, web crack or shaft crack. The frequency of the impacts is not given by the indicators, but usually is a sensitive indicator in itself.

It is often used on the remainder of the signal i.e. on the part of the signal where every nominal healthy signature has been removed. Meshing frequency and harmonics are, for example, removed before Kurtosis application, to focus on real defects rather than nominal impacts. Different techniques are available to cancel healthy signature.

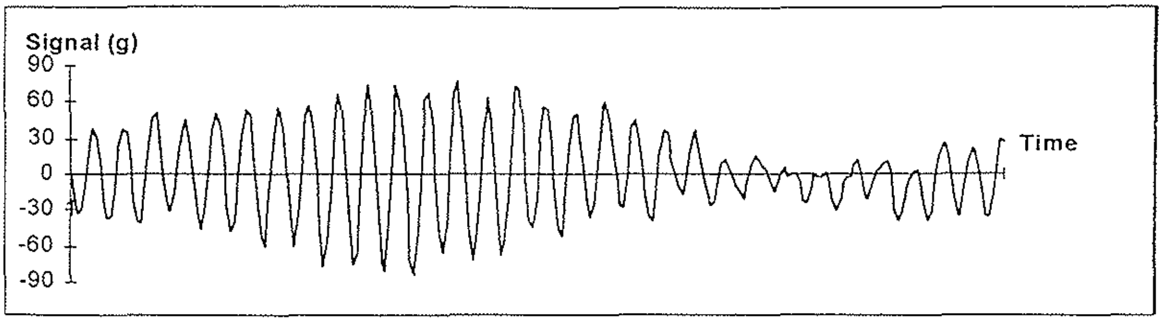
**Kg**: Squared deviation

This indicator is the standard deviation of the signal to standard deviation of the residual signal ratio. It clearly brings out multiples impacts, even with low energy, thus being a sensitive indicator used to detects defects such as tooth, hub, web or shaft cracks.

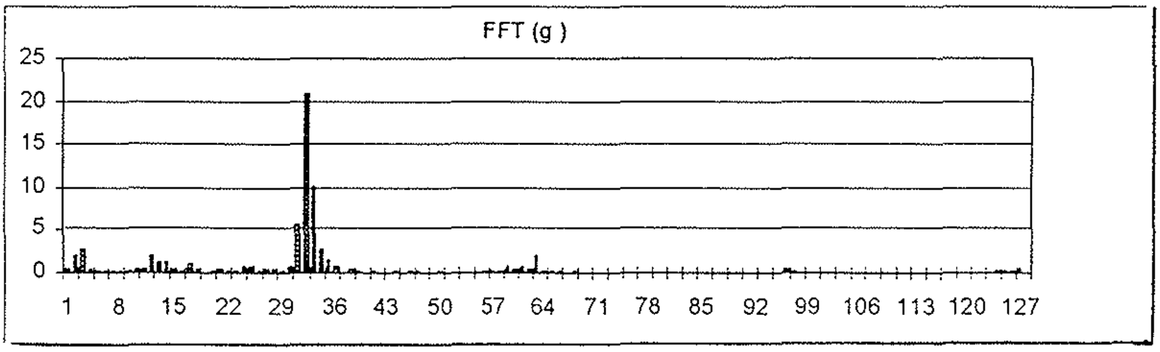
The above principles can be implemented in different ways not only because the electronic systems are not the same for, but also because many different algorithms can be used in the filtering field, in particular. Although these implementation specifics are of a prime importance to get efficient results, they are not described in this paper.

### 2.5.2 Reference records of healthy gearboxes

A reference record is made of the defect free gear box prior to starting individual tests. This record is used as a basis to properly assess the vibration signature evolution's with the seeded defect propagation. The following drawing shows the average signal and the spectrum of a reference gear record.




Signal Average



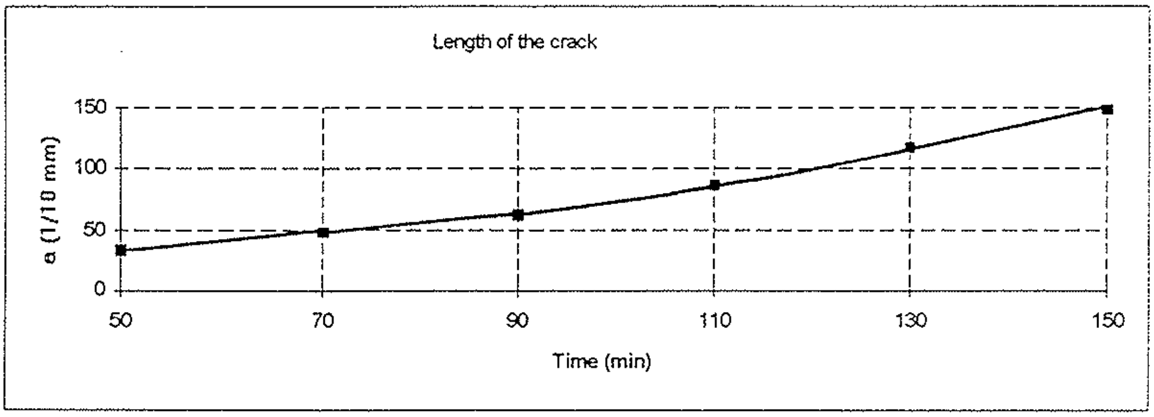

Spectrum for 1 gear

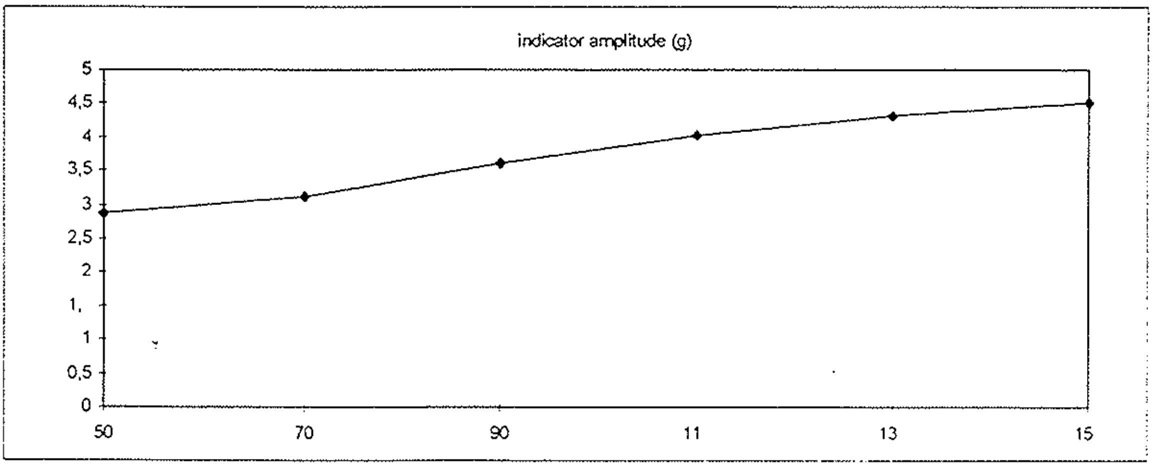
### 2.5.3 Correlation between crack propagation and indicator behaviour

Using the metallurgical analysis results, the crack propagation is drawn versus the bench time. That is possible thancks to the beach marks produced by the power level changes seen in the fracture topography. The following picture shows such 'beach marks'


MARKS ON THE FRACTURE TOPOGRAPHY

It is thus possible to relate both the crack propagation drawing and indicator behavior, and this provides a first indication as to r the indicator is sensible to the monitored defect. The following picture gives a shaft crack propagation curve as well as the 2Ω indicator and shows a good correlation between the two.




**indicator versus propagation**

**(shaft flexion caused by a crack, 2Ω indicator)**

### 2.6 First synthesis of vibration analysis detection capability

Although the programme is not yet finished, some indications can be given in the following table:

| type of failure | effect of failure | detection method |
|---|---|---|
| Shaft fracture | flexion, misalignement | good detection by energetic method |
| Shaft fracture | torsion | difficult detection by energetic methods.<br>could be improved by<br>-non stationnary methods<br>-modal frequency monitoring |
| Tooth fracture | | good detection by pattern analysis |
| web fracture | | good detection by pattern analysis |

## 3.Conclusion

The first objectives of the programme are to create a data base and assess the state-of-the-art in vibration analysis. These objectives are not yet complete because the programme is not yet finished. But it can already be said for EUROCOPTER part and as far as vibration analysis is concerned that the vibration technique already gives good results, leading to an improvement of the current HUMS TM * state of the art. In this programme, the best monitoring for bench safety has been provided by vibration analysis rather than by other techniques. It is however obvious that enhancements will have to be made. This current programme is used by EUROCOPTER as a basis for the necessary improvements, already partially implemented in the EUROHUMS TM *. EUROCOPTER is currently working in two directions:

The first one tends to have a more automated diagnostic with multiple indicators. Indeed, the operators will then not need any expertise to manage their maintenance with HUMS TM *. The second one is a fundamental study on new indicators for non stationary phenomena. A EUROCOPTER definition currently exists but is not yet applied

The programme has been limited to gears and shafts cracks. It has now been confirmed that this really was the step to start with. Vibration analysis seems to be the only technique efficient enough to monitor crack propagation and it was important that it be focused. It has been checked during the programme that debris monitoring or SOAP are not effective for this kind of defects. Some noise analysis trials have not provided interesting results neither.

A secondary -but no less important- objective is to participate in the HUMS TM * validation. In this framework, the data base is used to validate implementation of the algorithms in the computer. The other application is important too, since the results are being used at EUROCOPTER to validate its thresholds set up process.
This kind of result would have been difficult to obtain with a 'fatigue trial' where defects cannot be initiated so accurately. It has to be noted that the trials have always been performed at a nominal power level, so that the use of the results on crack growth rates is immediately available for HUMS TM * validation.

In parallel, some other helicopter parts need to be addressed in an equivalent systematic manner. They seem, to date, at least as important as the MGB gears and shafts for helicopter maintenance. Bearing and rotor monitoring now have to be integrated in a complete equivalent process including defect detectability and thresholds set-up based on component design and algorithm definition.

TM *: HUMS AND EUROHUMS are TELEDYNE CONTROLS TRADE MARKS