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# INVESTIGATION OF THE RANDOM COMPONENT AUTOCORRELATION IN THE PROCESS OF CUMULATING WIRE BREAKS IN HOISTING ROPES

**Summary.** This paper is an extension of the presentation of the investigations carried out in connection with the random component autocorrelation finding in the process of cumulating wire breaks in hoisting ropes. First paper [2] showed existence of the memory in the process and considered the mathematical consequences of it. This article tackles with the problem of the physical background of the phenomenon.

# BADANIE AUTOKORELACJI SKŁADNIKA LOSOWEGO PROCESU NARASTANIA LICZBY PĘKNIĘĆ DRUTÓW LIN NOŚNYCH

**Streszczenie.** Artykuł ten jest ciągiem dalszym prezentacji wyników badań związanych z istnieniem autokorelacji składnika losowego procesu narastania liczby pęknięć drutów lin nośnych. W pierwszej pracy [2] omówiono istnienie pamięci procesu i rozważano matematyczne konsekwencje tego zjawiska. Niniejsza praca rozważa problem fizycznego podłoża tego zjawiska.

## 1. Introduction

In the paper [2] existence of the random component autocorrelation in the process of cumulating wire breaks in mine hoisting ropes was stated. Let us recall shortly the main points of considerations.

The mathematical construction of the power function describing the process of wire breaks cumulating in time is:

$$n = \alpha\, t^{\beta}\, c^{\xi}, \tag{1}$$

where: $\alpha, \beta$ - structural function parameters,

$t$ - time,

$c$ - constant (in our case $c = e$),

$\xi$ - pure random component.

Transforming the above formula the pure random component can be defined as:

$$\xi = \ln\,[n/\alpha\, t^{\beta}\,] \tag{2}$$

The random component is not observable directly. Nevertheless when data of $< n_i, t_i >$; $i = 1, 2, \ldots$ type is gathered concerning a particular rope, the structural parameters can be assessed. Then

$$\xi_i = \ln [n_i / a (t_i)^b ] \tag{3}$$

where: $a$, $b$ are estimates of the structural parameters,
determines the time series of residuals which are the estimates of unknown random component realisation.

In paper [2] results of autocorrelation tracing for 15 hoisting ropes with triangle shape of strands were presented. In almost 70% of cases autocorrelation phenomenon was noted. The paper concluded that the observed phenomenon possesses its physical background as well as it has some mathematical consequences. The latter ones were considered in a comprehensive way but the physical aspect of the autocorrelation phenomenon was not considered; some suggestions were formulated only waiting for outcomes of further investigations.

The purpose of this paper is to show the results of further research concerning physical ground of this observable fact.

## 2. Physical and statistical hypotheses of the phenomenon

In the cited paper two possible reasons creating memory in the random component were formulated:

- the fatigue wearing process running in the metal wires of rope has such character,
- the construction of rope has such property which creates autocorrelation.

Let us notice that these reasons do not exclude each other, therefore they can exist simultaneously.

At the beginning a decision was made that two different types of rope construction will be taken into account - those of triangle shape of strands and the Warrington-Seale. They should be investigated in the same way. A possible influence of the rope construction on the memory in the process of wire breaks should be visible comparing results of tests for both types of rope structures.

Therefore the first formulated hypothesis $H_1$ was:

- the phenomenon of memory in the process of cumulating wire breaks in a rope is not only connected with the triangle shape of strands.

Before statistical investigation a careful analysis was made to find theoretical explanation of the phenomenon. The summary of it can be shown as follow.

In early seventies researchers tackling with process of fatigue cracks found (e.g. paper [5]) that in some cases subsequent increments in cracks are correlated with the neighbouring ones. The problem occurred difficult and its theoretical description complicated because it needs to employ many random variables correlated to each other in a general case. After more than ten years of investigation the idea of mathematical description of the phenomenon fluctuated to the model of marginal one-dimensional distributions shown with variance and covariance matrix (or correlation and autocorrelation matrix). The problem is briefly described by Sobczyk & Spencer in [9].

The general physical idea of the phenomenon is based on a concept that the fatigue accumulation can – in many cases – decrease the wire strength for further cracks (we can say that a rope *remembers* its failures) . If so, the autocorrelation of unit increments of failure magnitude should be observed. Immediately a new $H_2$ hypothesis comes into being:

- It should be a positive autocorrelation in the random component.

Moreover, observing the process of cumulating of wire breaks in a rope (which means growing rope degradation) we can formulate a hypothesis $H_3$ stating:

- the strength of autocorrelation should increase in time.

Verification of the above hypothesis requires rich data i.e. the records of total wire breaks must be of appropriate length. It allows to divide the time series into two or three equal parts and the values of autocorrelation coefficient counted for each part can be compared between themselves and obviously compared with corresponding critical values taken from the tables.

Author, being familiar with the difficult nature of the wear-and-tear process for hoisting ropes, great dispersion in data for the same type of rope working at the same shaft etc., formulated the last preliminary hypothesis $H_4$ saying:

- different working conditions existing in different shafts and existing dispersion in quality of ropes can significantly disturb (suppress) signs of regularities; the obtained results will have statistical sense only.

## 3. Investigations and results

As it was stated, two types of hoisting ropes were taken into account: the Warrington-Seale type and ropes of triangle shape of strands.

Because of high requirements concerning the verification of increment in autocorrelation strength only a long data has been taken into consideration. It reduces significantly the statistics being in possession; only ten sets of information remained.

Table 1 shows important information of a rope being investigated and results of statistical testing. In column *1* the number of a rope and a rope type is given (Δ - triangle strands rope, WS – Warrington-Seale rope). Column *2* called observation parameter, gives information how long a rope was observed; "*how long*" is expressed in hoist cycles or in days. In the next column the total number of observed breaks for a given rope is specified. Further columns *4* to *10* show information on statistical investigation. Column *4* contents the autocorrelation order. Depending on the length of time series observed the data has been divided into two or three equal parts and for each part the autocorrelation coefficient calculated (column *5, 7, 9*). Columns *6, 8, 10* presents critical values (taken for tables [12]) corresponding with appropriate empirical values. The assumed level of significance $\alpha = 0.05$. All empirical values of significant correlation, greater than critical ones are bolded.

Table 1

Results of autocorrelation investigation for hoisting ropes

| No Type | Observation parameter | Total No of breaks | Autocor Order | I observation part | | II observation part | | III observation part | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | autor coef | crit value | autor coef | crit value | autor coef | crit value |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 10 J | 107500 cycles | 236 | I | ***0,852*** | 0.432 | ***0,773*** | 0,432 | | |
| | | | II | ***0,789*** | 0,444 | ***0,589*** | 0,444 | | |
| | | | III | ***0,475*** | 0.455 | ***0,494*** | 0,455 | | |
| | | | IV | 0,167 | 0.468 | 0,271 | 0,468 | | |
| 13 J | 84000 cycles | 294 | I | ***0,766*** | 0,482 | ***0,657*** | 0,482 | ***0,978*** | 0.482 |
| | | | II | 0.485 | 0,497 | ***0,501*** | 0,497 | ***0,971*** | 0.497 |
| | | | III | 0,352 | 0,514 | 0,457 | 0.514 | ***0,937*** | 0,514 |
| | | | IV | | | | | ***0,896*** | 0,532 |
| | | | V | | | | | ***0,801*** | 0,553 |
| | | | VI | | | | | ***0,673*** | 0,576 |
| A 2 WS | 743 days | 59 | I | ***0,571*** | 0,468 | | | | |
| | | | II | 0,372 | 0,482 | | | | |
| A 1 WS | 781 days | 93 | I | ***0,612*** | 0,423 | | | | |
| | | | II | -0,101 | 0,433 | | | | |
| | | | III | 0,438 | 0,444 | | | | |
| | | | IV | ***-0,695*** | 0,455 | | | | |
| | | | V | **0.510** | 0.468 | | | | |
| N 1* | 688 days | 999 | I | ***0,966*** | 0,497 | ***0,899*** | 0,497 | ***0,992*** | 0,497 |
| | | | II | ***0,876*** | 0,514 | ***0,788*** | 0,514 | ***0,991*** | 0,514 |
| | | | III | ***0,742*** | 0,532 | ***0,665*** | 0,532 | ***0,985*** | 0,532 |
| | | | IV | ***0,566*** | 0,553 | ***0,683*** | 0,553 | ***0,992*** | 0,553 |
| | | | V | 0,363 | 0,576 | ***0,714*** | 0,576 | ***0,992*** | 0,576 |
| | | | VI | | | ***0,748*** | 0,602 | ***0,993*** | 0,602 |
| | | | VII | | | ***0,767*** | 0,632 | ***0,992*** | 0,632 |
| | | | VIII | | | ***0,779*** | 0,666 | ***0,991*** | 0,666 |
| N 2 | 359 days | 1713 | I | ***0,864*** | 0,468 | ***0,989*** | 0,468 | | |
| | | | II | ***0,585*** | 0,482 | ***0,986*** | 0,482 | | |
| | | | III | 0,272 | 0,497 | ***0,987*** | 0,497 | | |
| | | | IV | | 0,514 | ***0,98*** | 0,514 | | |
| | | | V | | 0,532 | ***0,984*** | 0,532 | | |
| | | | VI | | 0,553 | ***0,943*** | 0,553 | | |
| | | | VII | | | ***0,843*** | 0,576 | | |
| | | | VIII | | | ***0,669*** | 0,602 | | |
| N 3 | 302 days | 1735 | I | ***0,789*** | 0,497 | ***0,935*** | 0,497 | | |
| | | | II | ***0,531*** | 0,514 | ***0,949*** | 0,514 | | |
| | | | III | 0,256 | 0,532 | ***0,895*** | 0,532 | | |
| | | | IV | | | ***0,883*** | 0,553 | | |
| | | | V | | | ***0,947*** | 0,576 | | |
| | | | VI | | | ***0,871*** | 0,602 | | |
| | | | VII | | | ***0,973*** | 0,632 | | |
| | | | VIII | | | ***0,921*** | 0,666 | | |
| 13 | 336 days | 1294 | I | ***0,723*** | 0,482 | ***0,757*** | 0,482 | ***0,966*** | 0,482 |
| | | | II | ***0,505*** | 0,497 | ***0,601*** | 0,497 | ***0,951*** | 0,497 |
| | | | III | 0,341 | 0,514 | **0,582** | 0,514 | ***0,913*** | 0,514 |
| | | | IV | | | 0,496 | 0,532 | ***0,843*** | 0,532 |

| No Type | Observation parameter | Total No of breaks | Autocor Order | I observation part | | II observation part | | III observation part | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | autor coef | crit value | autor coef | crit value | autor coef | crit value |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| | | | VI | | | | | ***0,601*** | 0,576 |
| | | | VII | | | | | 0,584 | 0.602 |
| 14 | 723 days | 1112 | I | ***0,906*** | 0.497 | ***0,897*** | 0.497 | ***0,992*** | 0.497 |
| | | | II | ***0,861*** | 0,514 | ***0.888*** | 0,514 | ***0,991*** | 0,514 |
| | | | III | ***0,702*** | 0,532 | ***0.665*** | 0,532 | ***0.922*** | 0.532 |
| | | | IV | ***0.601*** | 0.553 | ***0.683*** | 0,553 | ***0,902*** | 0,553 |
| | | | V | 0.468 | 0.576 | ***0,714*** | 0,576 | ***0.872*** | 0.576 |
| | | | VI | | | ***0,611*** | 0.602 | ***0,703*** | 0.602 |
| | | | | | | 0.630 | 0.632 | ***0.639*** | 0.632 |
| 11 J | 61000 cycles | 288 | I | 0.471 | 0,553 | 0,08 | 0,553 | | |
| | | | II | 0,189 | 0,576 | 0,14 | 0.576 | | |
| | | | III | 0,259 | 0.602 | 0,072 | 0.602 | | |

Only data concerning the Warrington-Seale type of ropes were too short to be split into two.

## 4. First conclusions and comments

Information given by the above table is quite important, even at the first glance. It verifies majority of formulated hypotheses. We can summarize it in the following way.

1. Hypothesis $H_1$ saying *the phenomenon of memory in the process of cumulating wire breaks in rope is not connected with the triangle shape of strands rope only* is correct; actually we can formulate even stronger hypothesis $H'_1$ stating
   ***the phenomenon of memory in the process of cumulating wire breaks in rope is connected with the physical nature of hoist rope degradation***
   (notice that here in 90% of investigated cases characterised by rich statistical data autocorrelation exists!).
2. Hypothesis $H_2$ saying *it should be a positive autocorrelation in the random component* tells the truth for the ropes with triangle shape of strands only. This confirms additionally a well-known fact that the process of rope degradation for Warrington-Seale ropes has different character than for triangle strands ropes. Positive and negative autocorrelation here is being observed which means it should be a different physical background of such phenomenon.
3. The fourth hypothesis: *the strength of autocorrelation should increase in time* looks correct at the first glance but its statistical verification needs more advanced analysis which will be done in the next point of the paper.
4. Fortunately, in spite of the "fearing" hypothesis $H_4$, the phenomenon of memory has strong character. It occurs in majority cases. Further regularities will be traced in the next point and their statistical character will be verified accordingly.
5. The phenomenon of autocorrelation exists for both ways of counting of the working parameter: for days and hoist cycles.

## 5. Further statistical analysis

Let us now take under consideration the problem of the possible increment in the strength of autocorrelation for triangle strands ropes.

There are two problems to consider:

- in some cases value of autocorrelation coefficient for first part of observation (the earlier one) is higher than that for the further part (II or III).
  Does it mean that autocorrelation in such a case has decreasing character or this difference has a random character only?
- in some cases value of autocorrelation coefficient for the first part of observation is lower than that for the further part.

Does it mean that autocorrelation in such a case increases significantly ?

To solve the above problems we have to employ an appropriate statistical tool – a test. Fortunately we can find it in book [4].

Only two cases – examples - will be here presented to show the way how to solve these problems. Later the total summary allows us to get an idea on a general tendency.

Let us now take under consideration the case where the first autocorrelation coefficient $R_I = 0.852$ whereas the second one $R_{II} = 0.773$. Basing on the data in hand we verify the hypothesis $H_0$: $\rho = 0.773$ against the hypothesis $H_1$: $\rho > 0.773$. We employ the level of significance again $\alpha = 0.05$ assuming here that empirical correlation coefficient $r_a = 0.852$.

Let us now calculate the value of statistics $U$:

$$u = \{1.1513\log[(1+r_a)/(1-r_a)] - 1.1513\log[(1+\rho)/(1-\rho)] - \rho/2(n-1)\}\ (n-3)^{1/2},$$

where $n$ is the sample size. The statistics $U$ has the asymptotical standardised normal distribution N(0,1) provided that the hypothesis $H_0$ is true.
We have:

$$u = (1.1513*1.097 - 1.1513*0.893 - 0.773/40)*18^{1/2} = 0.914.$$

The critical value $u_\alpha$ is 1.64 [12]. Because $u = 0.914 < u_\alpha = 1.64$ therefore we have no grounds to reject hypothesis $H_0$. Now we can believe that the observed difference in values of correlation coefficient has random character only. This statement permits us to declare that we do not observe decrement in autocorrelation.

Let us now consider the case where value of autocorrelation coefficient for the first part of observation is lower than that for the further part, say $R_I = 0.723$ whereas the second one $R_{II} = 0.966$ (rope 13). Basing on the data in hand we verify the hypothesis $H_2$: $\rho = 0.723$ against the hypothesis $H_3$: $\rho > 0.723$. Assuming here empirical correlation coefficient $r_a = 0.966$.

Let us now again calculate the value of statistics $U$. Here we have:

$$u = (1.1513*1.762 - 1.1513*0.794 - 0.966/32)*17^{1/2} = 4.471.$$

Knowing the critical value, we have grounds now to reject hypothesis $H_2$ assuming $H_3$ says the truth. The above means the observed difference in values of correlation coefficient is significant. No doubt, the strength of autocorrelation increases.

## 6. General conclusion

Following the above way of statistical analysis the whole gathered results presented in

Table 1 were taken under statistical treatment if necessary. Obtained outcomes allow us to formulate the following statement:

- for triangle strands rope a positive autocorrelation in the random component usually exists; the strength of it increases in time (or: when number of hoist cycles increases); periodically the strength of autocorrelation remains constant.

## 7. Hypothesis concerning warrington-seal ropes

Let us recall that the degradation process for this type of ropes has different character than for triangle strand ropes. In the field of the memory in the process of cumulating of wire breaks the autocorrelation can be both positive and negative. The poor data being in possession does not allow to make more comprehensive analysis. Nevertheless we need here a physical hypothesis that can explain this phenomenon.

Whereas for positive autocorrelation in rope degradation we are in comfortable situation having clear and well communicative physical explanation, in connection with random crack increment with retardation situation is much worse. Literature concerning this topic is quite rich (see e.g. [1, 3, 6-8, 10, 11]) but the state of art here is well described by the following statement: "Although in literature a lot of models trying to describe this phenomenon by changing variety of constants, coefficients of strength intensity in Parias-Erdogan's equation exists; still very little was done towards a rational explanation of the problem" [10]. Generally, some authors are of the opinion that increment in crack with retardation is connected with overloading, especially when it is of a block type not a peak one. In some cases retardation is generated by squeezed type load. In other cases the phenomenon of retardation is associated with microstructure of material considered, although environmental factors have some power on it. Normally, it is difficult to isolate and distinguish the influence of a particular factor of speed of a crack increment. According to other opinions material ductility has significant importance on the phenomenon... Making a short summary of all these ideas we can say that there is a lot of possibilities and nobody knows which set of factors is the proper one.

Let us try to consider this problem from the mining practice.

At first, the only difference between these two types of ropes is their construction. The method of rope selection, calculation, value of factors of safety etc. are the same. The structure of a rope, configuration of wires and diameters are the main differences. They are the main source of the dissimilarity in the process of rope degeneration, taking into account that the rope environment is similar to that of triangle strands rope.

From the other hand, the negative memory occurs sometimes in further orders of autocorrelation and it interlaces with positive ones. Therefore it creates something like an auxiliary echo of a certain phenomena running in degraded metal wires. Perhaps, wires of smaller diameter are overloaded comparing to greater wires. Actually it is very hard to devise what is really running in Warrington-Seale type rope. No doubt it needs further extensive investigation.

## LITERATURE

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## Omówienie

Zjawisko autokorelacji istniejące w szeregu czasowym reszt procesu kumulacyjnego pękania drutów lin nośnych urządzeń wyciągowych zostało wykryte niedawno [2]. Matematyczne konsekwencje wpływu tej prawidłowości na proces estymacji parametrów strukturalnych, mierniki dobroci ich oszacowania, jak i na procedurę predykcji zostały omówione w pierwotnym artykule [2]. Przedmiotem rozważań niniejszej pracy są fizyczne aspekty tego zjawiska. Oprócz hipotez dotyczących właściwości samego procesu narastania liczby pęknięć drutów, jak i samej konstrukcji lin, kilka subtelnych hipotez statystycznych zostało tu sformułowanych w celu głębszej analizy tej pamięci procesu.

W wyniku przeprowadzonej analizy statystycznej wiele interesujących wniosków sformułowano podczas wyjaśniania podstaw fizycznych i następstw czasowych tego zjawiska. Niektóre zagadnienia nie zostały jednakże wyjaśnione i wymagają one dalszych badań w tym zakresie.