RELIABILITY CHARACTERISTICS OF MECHANICAL OBJECTS OF AGRICULTURAL MACHINES

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Abstract
Weibull distribution is commonly used as theoretical distribution of probability in the field of mechanical parts reliability. One of the advantages of using Weibull distribution is that the failure rate can have a rising, falling or constant trend. Weibull distribution is flexible and adaptable for data of all over a wide range. When processing data for all objects, it is necessary to keep track of the operation time to failure, cycles to failure, transport distance, mechanical stress or similar continuous or discrete parameters. It is not always possible to process with a complete data set. The purpose of the paper is to acquaint the readers with the method of processing data of reliability of mechanical parts of agricultural machines based on Weibull analysis of incomplete data of time to failure.

Key words*: reliability characteristics; Weibull distribution; machine dependability.*

INTRODUCTION

Quite often Weibull distribution is used theoretical distribution of probability during solve of question in field of reliability of mechanical parts. This distribution is applied to data modelling, regardless of whether the failure rate is rising, falling or constant. Weibull distribution is flexible and adaptable for data of all over a wide range. For all objects it is necessary to record the time to failure, cycles to failure, transport distance, mechanical stress or similar continuous or discrete parameters. (*Nassar, et al., 2017; Teringl, et al., 2015*). The method of data processing is focused on incomplete data in the paper. This method is demonstrated on the data of operation time to failure of the taper pins of the disc cultivators. This group includes cases in which there is no failure in all monitored objects during the monitored period (operational time). The processing of incomplete reliability data is typical for data collection in operation, because it is not possible to obtain information of all operating time to failure within a limited time interval in many cases. The Weibull distribution parameters obtained can also be used to apply theory of renewal for decision making between preventive maintenance and corrective maintenance. The aim of the article is to provide information about the reliability data processing when obtained data is not complete, which it means that many of the monitored mechanical parts are in operation state and have not failed.

MATERIALS AND METHODS

When analysing of reliability data, it is necessary to include data of objects that have not broken down during monitored period.

As an example of data processing was used incomplete data of operational time to failure of taper pins of the disc cultivators. A total of 92 machines were analysed and 35 machines failed. The disadvantage of the data obtained is the fact that there are no exact values of the operating time to failure. The operational time to failure *t* were determined only in intervals, as the area worked in hectares. Excessive damage or fracture of the taper pins of the disc cultivators was considered as a failure. Analysis object is excluded or censored if it has not been broken down by a given manner. If the objects are without a failure, then the data is called censored.

Types of censored data:
- censored by time - the test is terminated at the specified time *T* before than all objects are broken.
- censored by failure - the test is terminated when the specified number of failure.

When determining of point estimate of Weibull distribution parameters are followed of several steps:
- Ascending order of input data,
- Bernard's approximation,
- Substitution to modified distribution function *F(t)*,
- Linear regression – equation of line
- Calculation of shape α and scale β parameters of Weibull distribution *(ČSN EN 61649, 2009)*.

Firstly, it is necessary to sort the individual values in ascending order $i = 1, 2, 3, \dots n$. For the estimation of the distribution function *F(t)* is used order statistic with the median order (Table 1). Usually, Bernard's approximation is used to calculate the median order:

$$F_i(t) = \frac{i - 0{,}3}{n + 0{,}4} \tag{1}$$

Where: $F_i(t)$ – estimate of median value (-),
i – rank of serial number of time to failure t,
n – total number of failures.

In contrast, the calculation procedure for complete data is necessary to take into account of influence of censored data - modified procedure:

$$i_{t_i} = i_{t_{i-1}} + m_{t_i} \tag{2}$$

$$m_{t_i} = \frac{(n+1) - i_{t_{i-1}}}{1 + (n - m)} \tag{3}$$

$$F_i(t) = \frac{i_{t_i} - 0{,}3}{n + 0{,}4} \tag{4}$$

Where: m_{ti} – modified number of previous objects (events),
i_{ti} – adjusted number of time to failure t.

Then linear regression is used. This represents the approximation of values by least-square fit of a straight line. The following relations represent the derivation of calculations of the shape parameter α and the scale parameter β of Weibull distribution from the distribution function *F(t):*

$$F(t) = 1 - exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \tag{5}$$

$$1 - F(t) = exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \tag{6}$$

$$ln[1 - F(t)] = -\left(\frac{t}{\beta}\right)^{\alpha} \tag{7}$$

$$ln\left[\frac{1}{1 - F(t)}\right] = \left(\frac{t}{\beta}\right)^{\alpha} \tag{8}$$

$$ln\left\{ln\left[\frac{1}{1 - F(t)}\right]\right\} = \alpha \cdot \ln(t) - \alpha \cdot ln(\beta) \tag{9}$$

Tab. 1 Bernard's approximation of the function $F_i\ (t)$ and the calculation of the values for the *x*-axis and *y*-axis of time to failure *t* (partial data)

Number of event	Adjusted number of failure i_{ti}	Operational time to failure *t*	Event	Bernard's approximation $F_i(t)$	*x*	*y*
…	…	…	…	…	…	…
85	71,9714	750	Failure	0,7757	6,6201	0,4019
86	74,6000	750	Failure	0,8041	6,6201	0,4887
87	77,2286	750	Failure	0,8326	6,6201	0,5806
88	79,8571	750	Failure	0,8610	6,6201	0,6797
89	82,4857	1000	Failure	0,8895	6,9078	0,7895
90	85,1143	1000	Failure	0,9179	6,9078	0,9162
91	87,7429	1000	Failure	0,9464	6,9078	1,0734
92	90,3714	1500	Failure	0,9748	7,3132	1,3031

After simple mathematical modifications and two logarithms, the distribution function *F(t)* can be transformed into a line equation:

$$y = k \cdot x + q \tag{10}$$

where:
y – dependent variable,
x – independent variable,
k – slope of a line,
q – point of intersection of line with *x*-axis and *y*-axis, absolute term.

X-axis and *y*-axis are represented by (Table 1):

$$x = \ln(t) \tag{11}$$

$$y = ln\left\{ln\left[\frac{1}{1-F_i(t)}\right]\right\} \tag{12}$$

The least-square fit of a straight line is used to find the line equation, where it is necessary to solve a set of equation in a normal form:

$$q \cdot \sum_{i=1}^{n} x_i + k \cdot \sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} x_i\, y_i \tag{13}$$

$$n \cdot q + k \cdot \sum_{i=1}^{n} x_i = \sum_{i=1}^{n} y_i \tag{14}$$

Then, coefficient *k* and *q* can be count by:

$$k = \frac{n \cdot \sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \cdot \sum_{i=1}^{n} y_i}{n \cdot \sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2} \tag{15}$$

$$q = \frac{\sum_{i=1}^{n} x_i^2 \cdot \sum_{i=1}^{n} y_i - \sum_{i=1}^{n} x_i \cdot \sum_{i=1}^{n} x_i y_i}{n \cdot \sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2} = \overline{y_i} - k \cdot \overline{x_i} \tag{16}$$

By applying a set of equation in a normal form of linear regression, we obtain relation of linear function in the form:

$$y = 0{,}1933x - 6{,}5403 \tag{17}$$

It is also important to verify the statistical significance of the calculated regression equation. For this purpose is used coefficient of determination r^2, which it can be interpreted as the ratio of the sum of squares of the aligned (predicted) values and the sum of the squares of the observed values. (*Berrehal & Benissaad* 2016; Garmabaki, *et al.*, 2016)

Coefficient of determination r^2 is defined by:

$$r^2 = \frac{\left(n \cdot \sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \cdot \sum_{i=1}^{n} y_i\right)^2}{\left[n \cdot \sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2\right] \cdot \left[n \cdot \sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2\right]} \tag{18}$$

$$r^2 = \frac{\{35 \cdot (-130{,}377) - [-22{,}098 \cdot (-224{,}639)\}^2}{[35 \cdot 73{,}208 - (-22{,}098)^2] \cdot [35 \cdot 1445{,}052 - (224{,}639)^2]} = 0{,}678 \tag{19}$$

The coefficient of determination takes values between 0 and 1. If the coefficient of determination approaches 1, it is a strong dependence. Otherwise if the coefficient of determination approaches 0, it is a weak dependence. The standard recommends the calculations in which the *x* and *y* axes are swapped in the Figure 1.
The authors used Visual Basic for Applications for all calculations of parameters of Weibull distribution. Programmed algorithms can be used to easily calculate results when changing input data, which helps to refine reliability characteristics.
Values of Weibull distribution parameters (Figure 1) for time to failure *t* can be counted by

$$\alpha = \frac{1}{k} = \frac{1}{0{,}1933} = 5{,}173 \tag{20}$$

$$\beta = exp(q) = exp(6{,}5403) = 692{,}5 \tag{21}$$

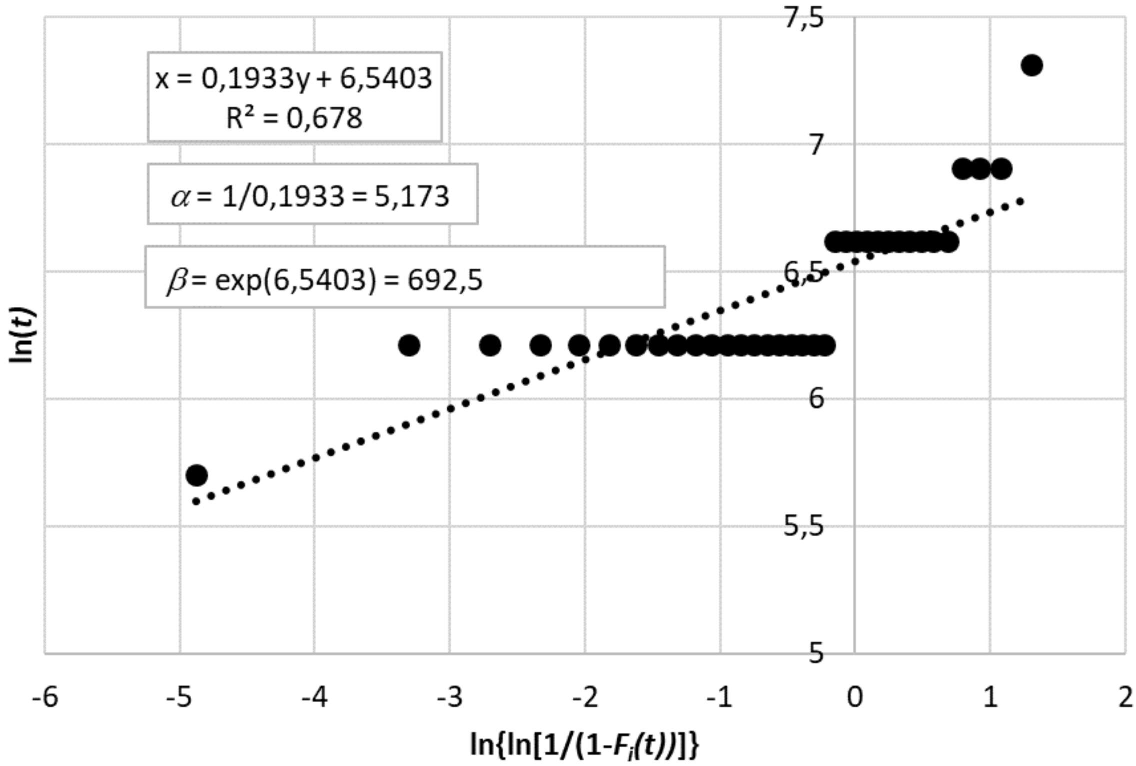

Fig. 1 Graph of calculation of equation of line by linear regression

RESULTS AND DISCUSSION

After calculation of values of Weibull distribution parameters can be used these parameters in calculation of reliability characteristics (service life):

- Probability density function of failure *f(t),*
- Probability of failure *F(t),*
- Reliability function *R(t),*
- Failure rate *λ(t).* (*Legat, et al., 2016*)

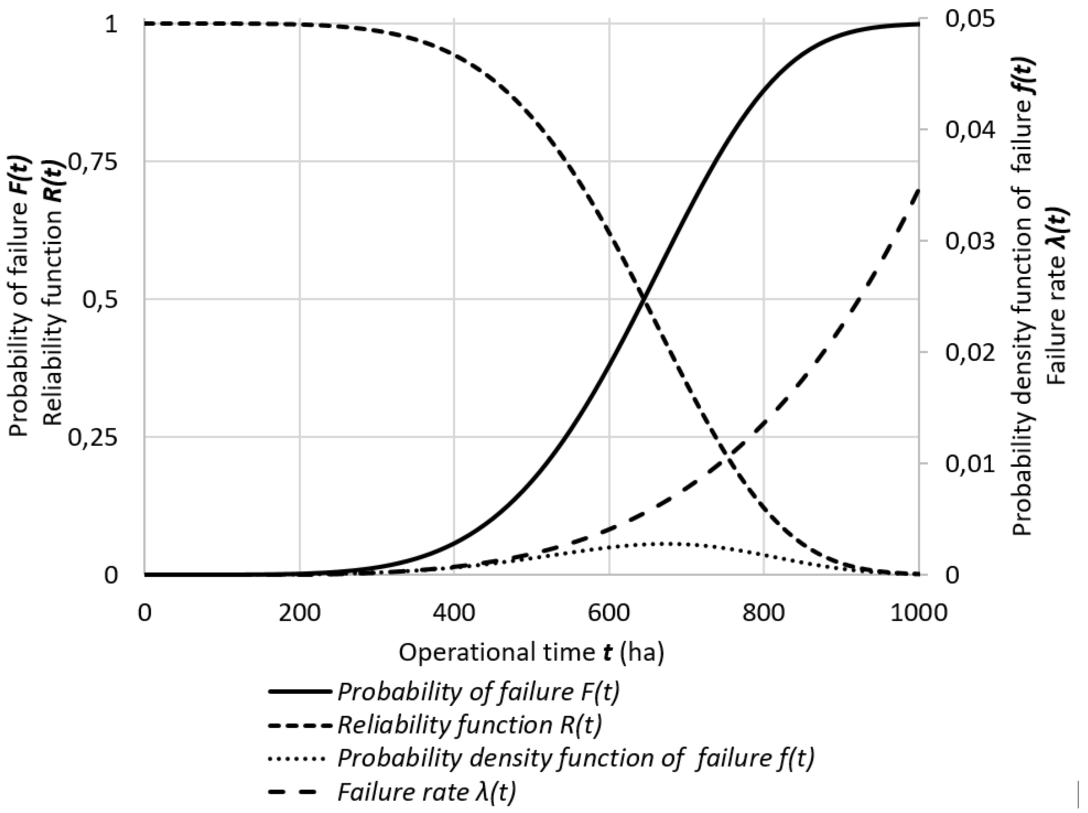

Fig. 2 Reliability characteristics *F(t), f(t), R(t), λ(t) for calculated Weibull distribution for shape parameter α=5,173 and scale parameter β=692,5*

For completeness, it appropriate to mention calculation of *MOTTF* (Mean Operating Time to Failure).

$$MOTTF = \beta \cdot \Gamma\left(1 + \frac{1}{\alpha}\right) = 692{,}5 \cdot \Gamma\left(1 + \frac{1}{5{,}1727}\right) = 637\ ha \qquad (22)$$

When calculation of *MOTTF* is necessary to use formula for function Γ – GAMMA in MS Excel. It is evident from the obtained reliability characteristics that the increase in the probability of failure is relatively steep and the monitored mechanical object has a low reliability, which is also evidenced by the low *MOTTF* value, which is 637 ha. Such low *MOTTF* is several times lower than commonly used objects of the same character. An equally important characteristic of reliability is failure rate, which represents the probability that a mechanical object that has not broken down to operational time *t* will break down immediately after operational time *t* (*Legat, et al., 2017*; Pacaiova *& Izarikova, 2019).* Too steep the course of the failure rate *λ(t)* is shown in Figure 2. It is obvious from the course of reliability characteristics that manufacturer of the disc cultivator must implement corrective actions to improve reliability parameters.

CONCLUSIONS

Weibull's analysis represents a suitable tool for determining the distribution of the probability density function of failure *f(t)*, respectively the distribution function of the probability of failure *F(t)* when processing of the reliability data of agricultural machinery systems. The paper presents one of the way of calculation of Weibull distribution parameters for an incomplete data, which is obtained from agricultural machinery operation. The results show that the calculated values of *MOTTF* are relatively low, which it is obvious from the reliability characteristics. In this particular case, the disc cultivator manufacturer made structural adjustments that resulted in a significant increase in machine operating life. Big weaknesses in general are input data, which are not always accurate and they are obtained in range of various intervals. With the development of modern technologies, it is assumed that there will be more suitable data collection from diagnostics sensors for already use processed algorithms. The main contribution of the authors is that they programmed automation of algorithms using the Visual Basic for Applications programming language in addition to the calculation methodology described. The computational algorithms created allow simple recalculation when new and more accurate data is obtained. The Weibull distribution parameters obtained can also be used to apply theory of renewal for decision making the between preventive maintenance and corrective maintenance.

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