



# Reliability of agriculture universal joint shafts based on temperature measuring in universal joint bearing assemblies

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## Abstract

This paper presents a research into reliability calculations of agriculture double universal joint shafts based on temperature measuring in cardan-type universal joint bearing assemblies. Special laboratory equipment was developed for this research which is presented in the paper. The objective of this research was to test the real life span of universal joint shafts in the laboratory and in field, to obtain the results which can be used to improve the reliability of universal joint shafts. If the presented research were used along with maintenance measures recommended in the paper and with proper use, the level of reliability of the shafts would be 2.1 times higher. The presented results of the research showed that needle bearings, *i.e.* bearing assemblies of the joints, are the most critical elements on universal joint shafts and are possible causes of their lower reliability. The second universal joint is the part with the lowest reliability in the observed technical system.

**Additional key words:** tractor; implements and attachments; needle bearings; maintenance; failure.

**Abbreviations used. Nomenclature:**  $f(t)$  (failure density function);  $MTTF$  (mean time to failures);  $R$  (reliability);  $R(t)$  reliability function;  $R_{eksp}$  (universal joint bearing assemblies reliability in the field tests);  $R_{eksp} Z$  (overall reliability of the shafts in the field tests);  $R_{eksp} Z_1$  (overall reliability of the first shafts in the field tests);  $R_{eksp} Z_2$  (overall reliability of the second shafts in the field tests);  $R_{opit}$  (universal joint bearing assemblies reliability in the laboratory tests);  $R_{opit} Z$  (overall reliability of the shafts in laboratory tests);  $R_{opit} Z_1$  (overall reliability of the first shafts in the laboratory tests);  $R_{opit} Z_2$  (overall reliability of the second shafts in the laboratory tests);  $t$  (failure time);  $Z_1$  (the first universal joint);  $Z_2$  (the second universal joint). **Greek letters:**  $\alpha$  (universal joint rotation angle);  $\alpha_{12}$  (rotation angle of the input shafts);  $\alpha_{23}$  (rotation angle of the output shafts);  $\lambda$  (failure intensity parameter);  $\lambda(t)$  (failure intensity function);  $\lambda_{eksp}$  (failure intensity in the bearing assemblies in the field tests);  $\lambda_{opit}$  (failure intensity in the bearing assemblies in the laboratory tests).

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## Introduction

Nowadays, agriculture is changing in response to the requirements of modern society, where ensuring food supply through practices such as water conservation, reduction of agrochemicals and the required planted surface, which guarantees high quality crops are in demand (Duarte-Galvan *et al.*, 2012). The necessary prerequisite needed to ensure what was previously said is the use of well-functioning agricultural machines and mechanisms. Agriculture universal joint shaft is a mechanism used in agriculture which has the lowest reliability so it may be a potential danger for agricultural equipment operators (Gligoric & Asonja,

2005). In the period from 2003 to 2013 there occurred four failures on double agriculture universal joint shafts reported in the Republic of Serbia. They were caused by fractured joints which occurred due to inappropriate maintenance and use. One of these accidents caused the death of one operator (Asonja *et al.*, 2013c). Similar accidents with the same outcome may occur with other means of transport, *i.e.* tanker trucks (Iowa FACE Program, 2002). The research conducted in the territory of the Autonomous Province of Vojvodina (Republic of Serbia) showed that injuries suffered by agricultural machine operators and workers made up 14.05% of the total number of reported injuries, and 16.86% of these injuries were caused by implements

and attachments (Mikov *et al.*, 2009). The life span of the agriculture universal joint shafts is between 5 and 9 years (Pastuhov & Timasov, 2009) and it depends on the size of the universal joint shafts, rotation angle  $\alpha$ , position of the shaft axle, load (torque), the state of the implements and attachments, maintenance, soil surface, etc. (Gligoric & Asonja, 2005). Unlike the agriculture universal joint shafts, other agricultural machines have a longer life span, *e.g.* the average life span of tandem axle tractors in the Republic of Serbia is 15 years (Nikolic *et al.*, 2008) while mineral fertilizer dispensers may operate as long as 11 years (Desnica *et al.*, 2007).

The main role of the universal joint shaft (presented and tested in this paper) is to transfer torque from a tractor to an implement or attachment, with axes of joint shafts forming a rotation angle  $\alpha$  with a permanent or variable value (Asonja *et al.*, 2013a). The universal joint power transmissions in agricultural machines may constantly vary depending on the soil surface roughness which ultimately may cause damages or losses during operation (Golpira *et al.*, 2013). Today, universal joint shafts play an important role in torque transfer from the operating machine (tractor) to the implements and attachments. The torque and the power of the tractor are mainly transferred mechanically by means of the universal joint shaft to almost all the implements and attachments (presses, seeders, mineral fertilizer dispensers, potato diggers, etc.). This ongoing research topic indicates the necessity of use and also the widespread use of agriculture universal joint shafts because it has been estimated that there are over 500,000 agriculture universal joint shafts currently in use only in Serbia, *i.e.* there is one agriculture universal joint shaft used per 16 people (Asonja *et al.*, 2013b).

In 80 to 90% of the cases the life span of the universal joints in agricultural machines, vehicles, tractors and other equipment using universal joint is limited by deterioration of their operating capacity. According to the outcomes of research on agricultural machines of today, 14% of failures in mechanical transmissions appears in universal joint power transmissions embracing about 60% of shaft failures (Tavlybaev, 1991; Erohin & Patuhov, 2008). The most common transmission failures are caused by faults in manufacturing,

design and maintenance, followed by raw-material defects and user-related faults (Bayrakceken *et al.*, 2007; Godec *et al.*, 2009).

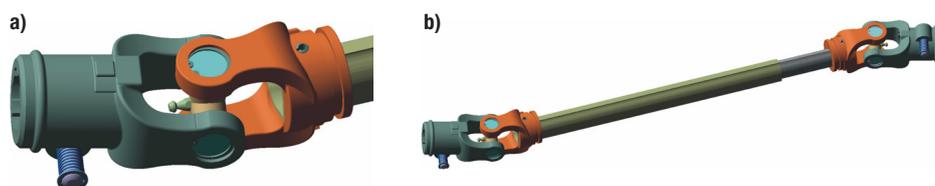
Reduction in failure-free operation of cardan-type universal joint in agricultural machines is caused by deterioration of its operating capacity when used in field, because its basic elements tend to fail due to destruction-causing wear. The mentioned consequences cause the occurrence of radial, axial and circular clearance in the “crosshead sleeve – needle bearing” joint resulting in element deformation in bearing assemblies.

The purpose of this research was to investigate the real life span of agriculture universal joint shafts in the laboratory tests and in the field tests, and to use this reliability research to establish if it is possible to expand their life span. The main hypothesis was that appropriate maintenance and operation may considerably improve the reliability.

## Material and methods

Investigation of the reliability of the agriculture universal joint shafts do require diagnostic testing of the state of bearing assemblies (needle bearings, crossheads and cups) of the joints. The method of temperature measuring in bearing assemblies was used to assess reliability of universal joint shafts (universal joints). A standard model of “double universal joint shaft” size I was used in the research. Fig. 1 shows both the investigated universal joint and the investigated agriculture double universal joint shaft in 3D, modelled by CATIA V5 software.

The investigation of universal joint shaft reliability was carried out in a laboratory (laboratory tests) and in field (field tests). A total number of 6 universal joint shafts were included in the investigation. The first three samples were tested in the laboratory, while the other three samples were tested in the field under operation conditions. The samples were investigated diagnostically after every 4 operation hours; however, the field samples were brought onto the test bench for observation in order to assess their level of reliability. The time needed to move the samples from the field



**Figure 1.** The investigated mechanism presented in 3D: a) universal joint and b) double universal joint shaft in “Z” performance.

to the test bench, or the speed at which they are moved, were not limited. Diagnostics of investigation of the field samples lasted for 10 minutes. The method of temperature measuring was used for investigation of diagnostics of the universal joint bearing assemblies condition. A laser infrared thermometer was used for the purpose. A criterion for assessment of universal joint shaft reliability depending on the temperature in the bearing assemblies was in accordance with the data given in Table 1. Every time the temperature was over 73°C, it was the indication that a failure occurred (Table 1).

The main technical and technological properties of testing were the following: (i) the universal joint shafts operated in “Z” performance; (ii) during testing the deflection angle was fixed to  $\alpha_{12}=\alpha_{23}=20^\circ$ ; (iii) the rotational speed was 540 rpm; and (iv) the joints were subjected to a power range 2-4 kW (36.15 - 74.86 Nm).

The tests were carried out in the period from 14 June 2007 until 26 November 2013.

### Investigations in the field

The investigations of the reliability of the universal joint shaft in the field were carried out in privately-owned farms in the territory of the Autonomous Province of Vojvodina in the Republic of Serbia. The farmers used the investigated shafts while cultivating their land parcels of 10 ha. The investigated shafts were driven by IMT 539 tractors with the nominal engine power of 29.5 kW.

The reliability investigation in the field was performed using three samples of universal joint shafts and every sample was owned by only one farmer. During the field tests the universal joint shafts were used for implements and attachments (field sprayers and mineral fertilizer dispensers). The mechanical connection between a tractor and implements and attachments was in compliance with the standard ASABE/ISO 21244:2011. The torques used in power transmission in these machines were identical to those used later on the test bench.

### Laboratory investigations

Laboratory method of the universal joint shafts reliability investigations was used as one of the most suitable methods to determine the reliability properties. For the purpose of the said investigations, a test bench was designed, model ANA, type 23-26-26-04 (Asonja *et al.*, 2012). An electric brake used for load simulation, model EK, type 6/28 (Asonja *et al.*, 2012) was designed

**Table 1.** Limit values in assessing conditions of universal joint bearing assemblies depending on their temperature (Asonja *et al.*, 2013a)

Bearing temperature	Bearing condition
< 62°C	Satisfactory condition
62-73°C	Dissatisfactory condition (warning)
> 73°C	Undesirable condition

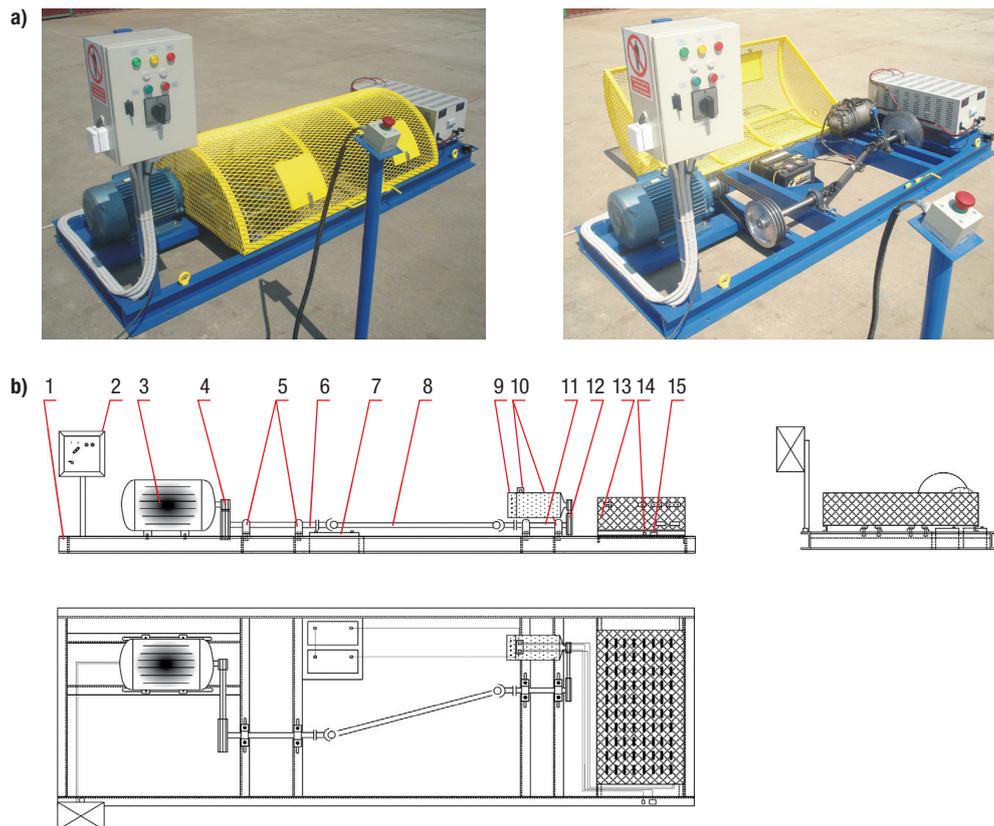
and used on the workbench especially for this investigation. Fig. 2a shows the test bench with the closed/open protective grid.

The main parts of the test bench (Fig. 2b) are: 1, steel frame; 2, main power distribution cabinet for the power supply of the electric motor and the load control system; 3, drive (electric motor); 4, belt drive; 5, bearing units on the first auxiliary shaft; 6, the first auxiliary shaft; 7, batteries; 8, tested universal joint shaft; 9, direct current (DC) generator; 10, bearing units on the second auxiliary shaft; 11, the second auxiliary shaft; 12, belt drives on the brake system; 13, load control system; 14, manual control of the DC generator excitation; and 15, control lamp of the DC generator excitation. The schematic diagram does not include the workbench protection system and the mobile stop button system to ensure a simplified presentation.

The research conducted during the lab tests using the test bench represents the real achievable field operation conditions in which agriculture universal joint shafts are usually used. The operating characteristics (rotation angle, power, rotational speed, etc) which correspond to some of them found in practice were simulated in the laboratory and they were also used to test the reliability of the samples. The laboratory investigations ensured the universal joint shafts tested at a rotational speed of 540 rpm, up to 300,000 revolution cycles, which corresponds to a testing life span up to ~300 operation hours. A variable power load in predetermined cycles of 50 operation hours was used during the tests. The said power load are those used in the field, namely, it is the power needed for implements and attachments drive (2, 3 and 4 kW).

### Research into the universal joint shaft reliability

A mathematical approach based on the analysis of diagnostic values of temperature in the universal joint bearing assemblies was presented to investigate the reliability of the shafts. Exponential distribution was used for the research, *i.e.*, failure intensity, mean time to failure and other values were defined. The obtained



**Figure 2.** Test bench (model ANA, type 23-26-26-04) with the closed/open protective grid (a). Schematic diagram (b) of the test bench “ANA” for investigation of universal joint shaft reliability (1, steel construction; 2, main electrical control box; 3, electric motor; 4, gears on the drive belt area; 5, bearing units on the first additional shaft; 6, the first auxiliary shaft; 7, batteries; 8, the laboratory shaft; 9, direct current (DC) generator; 10, reservoir units on the second auxiliary shaft; 11, second auxiliary shaft; 12, belt conveyors at brake part; 13, regulation system load; 14, manual control of the generator excitation DC; and 15, control lamp excitation DC generator).

investigation outcomes (using the laboratory and the field samples) and the application of appropriate mathematical functions resulted in adequate functions of universal joint bearing assemblies reliability used to show the rules of operation of a universal joint, considering the possibility of malfunction.

Reliability function and failure intensity function are unique, *i.e.*, a specific reliability function corresponds to a single specific failure intensity function, and vice versa (Jevtic *et al.*, 2011). Failure density function in the case of exponential distribution is referred to in Eq. [1] (Adamovic & Voskresenski, 2008):

$$f(t) = \lambda e^{-\lambda t}, \quad t \geq 0, \quad \lambda > 0 \quad [1]$$

where  $\lambda$  is failure intensity parameter and  $t$  is failure time.

Reliability function  $R(t)$  may be represented in Eq. [2]:

$$R(t) = e^{-\lambda t} \quad [2]$$

Failure intensity function may be given by Eq. [3]:

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda \quad [3]$$

Accordingly, in the case of exponential distribution, the failure intensity does not depend on the time and it always has a constant value. It is a very favourable circumstance which simplifies calculation in cases when exponential distribution may be applied. Consequently, when parameter  $\lambda$  of exponential distribution is determined, the failure intensity value is determined simultaneously. The failure intensity may be represented by a straight line.

The expected time of failure-free operation is equal to the reciprocal value of failure intensity  $\lambda$ . This value is often denoted as *MTTF* (Mean Time to Failure), and may be given by Eq. [4] (Adamovic & Voskresenski, 2008):

$$MTTF = \frac{1}{\lambda} \quad [4]$$

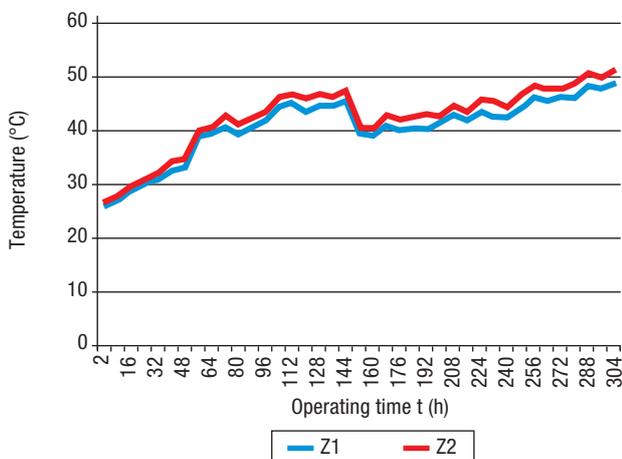
This is yet another favourable circumstance of exponential distribution because when failure intensity  $\lambda$  is determined, the value  $MTTF$  may easily be determined, and viceversa.

## Results

The agriculture universal joint shafts in laboratory tests withstood 304 operation hours without any visible damages, while the samples tested in field withstood 139 operation hours. The time of undisturbed operation shows that for the period of 5 years, which is the approximate life span of this type of joints, an average use could be 29 operation hours per year, which is a very short life length. However, the adequate maintenance and the appropriate use may considerably extend their life span.

Based on the results of the investigation of universal joint shafts in the laboratory, a diagram was developed (Fig. 3) with the mean values of temperature in the first and the second universal joint bearing assemblies. The Fig. 3 shows that at every moment of testing, the values of temperature of the second joints ( $Z_2$ ) were greater than those of the first joints ( $Z_1$ ). These data lead to the conclusion that the second universal joint is more loaded and is a cause of possible unreliability of double universal joint shaft.

The difference between the mean temperatures in bearing assemblies of the first joints and the second joints measured while operating in the field was regarded as the ultimate period of pre-failure condition of bearing assemblies of the first joints. Fig. 4a shows total average reliabilities for the observed diagnostic parameters of temperature in the bearing assemblies of the first joints in the laboratory and



**Figure 3.** The mean values of temperature in universal joint bearing assemblies during laboratory testing.

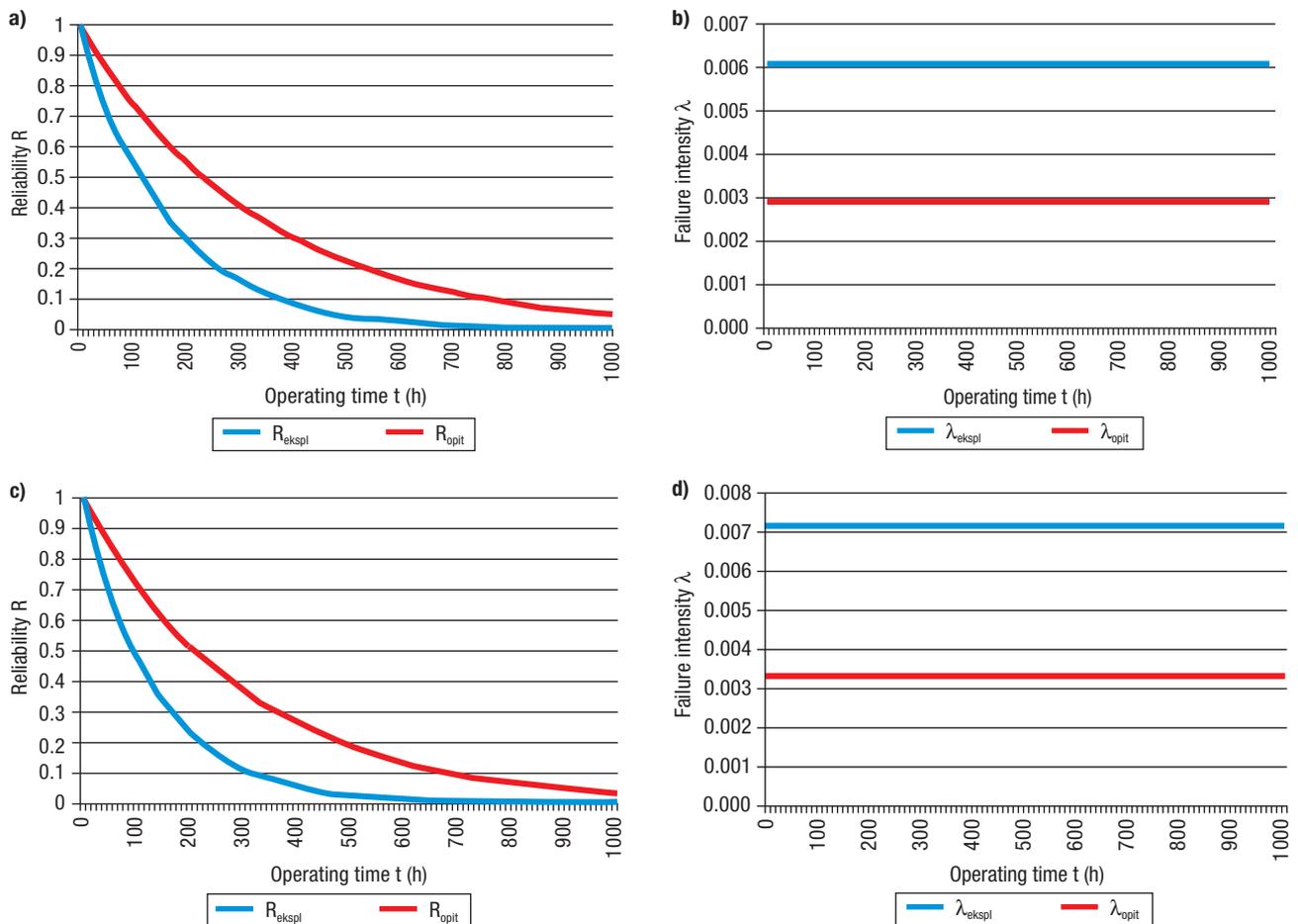
field tests. Considering Fig. 4a it can be concluded that the bearing assemblies of the first joints would reach the reliability of 10% for  $\sim 773$  h in the laboratory tests, while those in the field tests would reach the same reliability for  $\sim 380$  h. The  $MTTF$  in the bearing assemblies of the first samples in the laboratory tests would be  $\sim 336$  h for temperature parameters. Fig. 4b shows the failure intensity in bearing assemblies of the first joints in the laboratory and the field tests.

Fig. 4c shows the overall average reliabilities for the observed diagnostic parameters of temperature in the bearing assemblies of the second joints in the laboratory and in the field tests. Considering Fig. 4c it can be concluded that the bearing assemblies of the second joints would reach the reliability of 10% for  $\sim 696$  h in the laboratory tests, while those in the field tests would reach the same reliability for  $\sim 320$  h. The  $MTTF$  in the bearing assemblies of the second joints in the laboratory tests would be  $\sim 302$  h for temperature parameters. Fig. 4d shows the failure intensity in the bearing assemblies of the second joints in the laboratory tests and in the field tests.

The final investigation of the overall reliability of the double agriculture universal joint shafts based on the average reliabilities of the observed diagnostic parameters of temperature in the first joints and in the second joints in the laboratory tests and in the field tests are shown in Fig. 5a and 5b. Fig. 5a shows that the average predicted universal joint shaft reliability of 10% in the laboratory tests ( $R_{opit} Z$ ) would be  $\sim 366$  h of operation, the reliability of only the second joints ( $R_{opit} Z_2$ ) would be  $\sim 697$  h, while the reliability of the first joints ( $R_{opit} Z_1$ ) would be  $\sim 773$  h. Fig. 5b shows that the average universal joint shaft reliability of 10% in the field tests ( $R_{ekspl} Z$ ) would be  $\sim 174$  h of operation, the reliability of only the second joints ( $R_{ekspl} Z_2$ ) would be  $\sim 321$  h, and of the first joints ( $R_{ekspl} Z_1$ ) would be  $\sim 380$  h.

## Discussion

The research into reliability presented in the paper in the form of technical diagnostics was based on the observed principle of variation of measured diagnostic parameters on the laboratory and the field samples of the shafts, which resulted in obvious difference in variation of reliability. It is clear that the difference is considerable and occurred as a result of ineffective maintenance (inadequate lubrication, cleaning and protection), inadequate use (the rough soil surface may result in misalignment of rotation angles of the input shafts  $\alpha_{12}$  and rotation angle of the output shafts  $\alpha_{23}$ ,



**Figure 4.** The overall reliability (a) and failure intensity (b) of bearing assemblies of the first tested joints in laboratory and operating testing conditions. The overall reliability (c) and failure intensity (d) of bearing assemblies of the second tested joints in the laboratory and field tests.

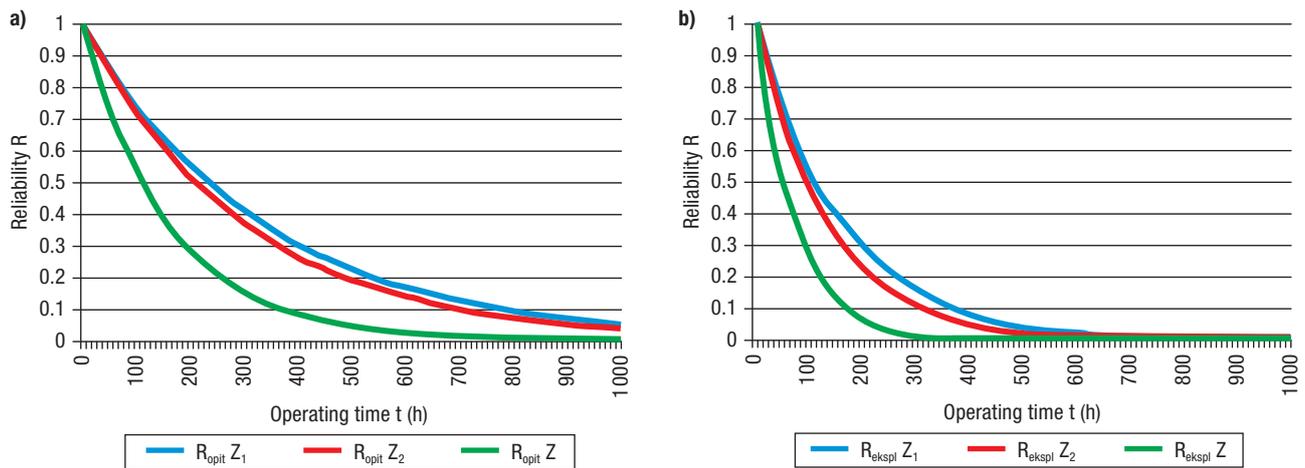
which leads to the increase of inertial force and the moment of inertia) and the complex conditions of agricultural production (dust, mud, wind, rain, etc). The presented results of the research observed through diagnostic parameters of temperature of the universal joint bearing assemblies, showed the extent to which the level of reliability of universal joint shafts, *i.e.* the reliability of the agriculture double universal joint shafts may be improved.

The following measures should be undertaken to reach the recommended reliability referred to in the paper:

— *Maintenance*: lubrication of the bearing assemblies (it should be done after 8 hours of continuous operation, or longer; if the periods of operation were shorter than 8 hours, the lubrication should be done before each use), detailed cleaning and washing of joints after each use, protection of the mechanisms with plastic protective coatings, protection of the entire mechanism against the effects of weathering during the non-use period, etc;

— *Use*: the appropriate assembling of the mechanism in compliance with the recommendations of the manufacturer of implements and attachments, providing appropriate overlapping of the telescopic shafts during operation, avoiding acute angles during operation, allowing rotation of the shaft only to one side, ensuring that the joints keep the same position during the uses that follow the first assembling of the shaft, the rotation angle must not be bigger than 20°, direction of rotation and the rotational speed of the mechanism should be adjusted to the implements and attachments, etc.

If the results of the research were applied according to *MTTF*, the predicted reliability of the universal joint shafts while operating in the field (in the moment of pre-failure reliability of 10%) could be ~2.10 times higher and it would be ~366 h (Figs. 5a and 5b). If the predicted reliability is observed for each joint separately, then it could be ~2.03 times higher for the first joint and it would be ~773 h, while for the second universal joints it could be ~2.17 times higher and it would be ~697 h (Figs. 5a and 5b).



**Figure 5.** Average reliability of joints (shafts) in (a) laboratory and in (b) field tests.

The failure intensity occurrence in the laboratory samples was  $\sim 0.003$ , while in the field samples it was  $\sim 0.006$  (Fig. 4b). The failure intensity occurrence in the field samples of the shafts on the first joints was  $\sim 0.003$ , while in the field samples it was  $\sim 0.0072$  (Fig. 4d). Insufficient level of technical maintenance, primarily of lubrication (which should be done every 8 operation hours), is one of the main reasons of lower reliability of the field samples; other reasons are the complex conditions of agricultural production, inadequate use, unprotected mechanisms in the period when they are not used, etc.

Other key results of the investigation of the agriculture universal joint shafts reliability are the following: (i) the second universal joint on the double universal joint shaft is the part which fails the first; (ii) when operating in the field, the mean temperature of the second universal joint shafts in the pre-failure condition was higher than the mean temperature of the first ones by 19%; (iii) very low reliability and a short life span of the agriculture universal joint shafts in the field are the result of inadequate technical maintenance and use as well as the complex conditions in agricultural production; (iv) the deflection angle of the double universal joint shafts being  $20^\circ$ , the leakage of the grease from bearing assemblies was noticed at both joints, even at the minimum load of 36.15 Nm, which was the result of a high level of vibrations; and (v) the laboratory samples withstood 304 operation hours without any visible damages, while the field samples withstood 139 operation hours on average.

While investigating the reliability of the agriculture universal joint shafts, Pastuhov (2008) obtained similar results. He investigated the reliability of the agriculture universal joint shafts of size IV on the test bench at the rotational speed of 1000 rpm and at different loads, and he noticed that at the deflection angle

of joints of  $\alpha=10.5^\circ$  the *MTTF* was 452 h, while at the deflection angle of  $\alpha=12^\circ$ , the *MTTF* was 395 h.

The hypothesis stating that the appropriate maintenance measures may considerably raise the reliability level of the universal joint shafts was confirmed. The future researchers of the reliability of agriculture universal joint shafts could use the conducted investigations because they indicate the following: the actual low reliability of universal joint shafts in operation; higher level of reliability (life span) of bearing assemblies which may be reached by appropriate technical maintenance and use; the possibility to use the results of the research on other universal joint shafts and other mechanical power transmitters; consideration of the problems of damages on bearing assemblies could increase the cost-effectiveness by extension of the life span of the universal joints in agricultural machines; and improvement in safety conditions for agricultural equipment operators.

As conclusions, the presented material in the paper is a real contribution to researches into reliability of universal joint shafts. There is a growing attention given to the problems of researches into reliability of universal joint shafts in the world. It is becoming interesting for scientists and professionals because it is the area which includes several scientific fields, which gives it a multidisciplinary character. Based on the scientific, material and other proofs presented in the paper, it seems that this problem is not considered enough in practice.

The presented results of the research showed that needle bearings, *i.e.* bearing assemblies of the joints, are the most critical elements on universal joint shafts and are possible causes of their lower reliability. The second universal joint is the part with the lowest reliability in the observed technical system. Within the experimental part of the research in the laboratory tests,

it has been proved that the investigated samples of double universal joint shafts reached the recommended life span of 304 h, while those in the field tests reached the life span of 139 h. Using the results of the research, the reliability of the universal joint shafts in field could be increased and it could be ~2.10 times higher (with pre-failure reliability of 10% in the moment of time). If the reliability is observed for each joint separately, then it could be ~2.03 times higher for the first joints, while for the second universal joints it could be ~2.17 times higher.

The presented research into reliability is based on analysis of diagnostic parameters of temperature in the bearing assemblies and it is a novelty in defining reliability of these types of mechanical power transmitters. It would be justified and reasonable to use them in analysis of reliability on other mechanical power transmitters.

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