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RELIABILITY ANALYSIS OF CRANE LIFTING MECHANISM

Summary. This paper focuses on a reliability analysis of various structural variants of a crane lifting mechanism. The reliability of such a mechanism is a basic requisite for the safe operation of the crane as a whole. The article analyses and jointly evaluates structural solutions for the lifting mechanism in a bridge crane, in order to emphasize the technical aspects of system reliability in this context.
Keywords: lifting mechanism, crane, reliability, technical system, reliability indicators, block diagram

1. INTRODUCTION

In the area of transport and handling machines or machinery, there are many devices with a high potential of danger or technical risk. The lifting mechanism of cranes, which are used, for example, in the transport of hazardous substances, is representative in this regard. It is possible to improve the reliability of such devices by taking various measures, e.g., by

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slowing the process of deterioration, eliminating the source of deterioration, following the procedures for operation and maintenance, and using alternate components.

A growing number of components in complex technical systems, however, has increased the probability of failure. Given that it is usually possible to improve the indicators of system reliability by carrying out several appropriate measures, finding a structural solution is very important too.

To perform a quantitative analysis of technical system reliability by using reliability indicators, mathematical methods of probability and statistical probability are applied. The most relevant methods used for the evaluation of structural reliability, including the theoretical basis of these methods, are described in [1,2,3]. A specific approach to reliability is presented in [4], whose authors derive the value of reliability from the scheduling of an activity with a random duration, such as travel under congested conditions, concerning questions related to transport. The ability to forecast machinery failure is vital in order to reduce maintenance costs, operation downtime and safety hazards. A novel approach to incorporating information on population characteristics and suspended condition trending data on historical units into prognoses is presented in [5,6]. A comprehensive, up-to-date description of all the important methods for the design, development, manufacture and maintenance of reliable engineering products and systems can be found in [7,8,9]. Another important aspect of machine reliability is the reliable maintenance or influence of maintenance on the reliability of machines and machinery [26,27,28,29,30,31,32]. Reliability-centred maintenance is a method for maintenance planning developed within the aircraft industry and later adapted to several other industries and military branches. This method is demonstrated in [10,11].

The reliability aspects of dynamic systems relating to engineering production plants are described in [12], while a reliability analysis of technical systems, which considers working environment parameters, is presented in [13].

A special approach to the questions of reliability is required in the case of driving systems equipped with piston combustion engines. Typical examples illustrating this investigation area can be found in [14,15].

The most important mechanism in every crane is the lifting mechanism. The motion of a crane lifting mechanism is considered in [16,17]. A special example of the crane lifting mechanism, which is installed in a quay container crane, is modelled in [18]. Questions concerning the bridge crane load spectrum and load distribution are analysed in [19,20]. An intelligent anti-swing control for the bridge crane is introduced in [21,22].

This article analyses and evaluates the technical system reliability relevant to the standard variants of a crane lifting mechanism, which is typically installed in bridge cranes.

2. METHODS USED FOR CALCULATING RELIABILITY INDICATORS IN TECHNICAL SYSTEMS

A system refers to a device, which consists of multiple parts, known as system components. It is important to understand its structure and the nature of its work to such an extent that we are able to determine whether or not the failure of a particular component will cause the entire system to fail. The system of our inquiry, which consists of n components, can be divided into series, parallel and combined configurations.

The reliability of a technical system that consists of components can be conveyed numerically by using the following indicators of system reliability, [23,24]:

F(t) – failure probability (unreliability
R(t) – failure-free probability (reliability)
f(t) – failure probability density
λ(t) – failure intensity

In order to calculate the reliability indicators of a technical system, it is necessary:

- To know the probability of a failure-free operation for $r_i(t)$, for i = 1, 2, ..., n components.
- To draw a reliability block diagram. A reliability block diagram illustrates how the components are interconnected in terms of reliability analysis and calculation.
- To assume that the individual parts are independent. This means that the failure, or rather the survival, of a particular system component does not affect the failure, or rather the survival, of other system components. Based on this simplification, we can determine the reliability of fundamental component interconnections.

2.1. Series systems

Series interconnection is a configuration of components in a reliability block diagram, in which a system failure occurs when at least one component fails. A reliability block diagram for a series system is shown in Figure 1.

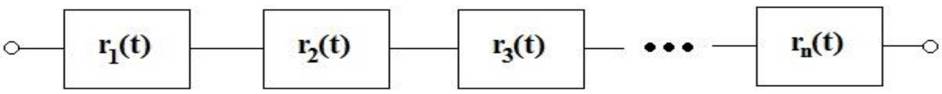

Fig. 1. Reliability block diagram of series interconnection

Reliability indicators for series systems are calculated by using the following formulas:

Probability of a failure-free operation in series systems

$$R(t) = r_1(t) . r_2(t) \ ... \ r_n(t) = \prod_{i=1}^{n} r_i(t) \tag{1}$$

Probability of failure in series systems

$$F(t) = 1 - R(t) = 1 - \prod_{i=1}^{n} r_i(t) \tag{2}$$

Failure probability density in series systems

$$f(t) = \frac{dF(t)}{dt} = -\frac{dr_1(t)}{dt} . r_2(t) \ ... \ r_n(t) - r_1(t) . \frac{dr_2(t)}{dt} . r_3(t) \ ... \ r_n(t) - ... - r_1(t) . r_2(t) ... r_{n-1}(t) . \frac{dr_n(t)}{dt}$$

Each element is expanded by quantity $\frac{r_i(t)}{r_i(t)}$, for i = 1, 2, ..., n. Then:

$$f(t) = -\frac{dr_1(t)}{dt}.\frac{r_1(t)}{r_1(t)}.r_2(t)...r_n(t) - r_1(t).\frac{dr_2(t)}{dt}.\frac{r_2(t)}{r_2(t)}.r_3(t)...r_n(t) - ... -$$

$$- r_1(t).r_2(t)...r_{n-1}(t).\frac{dr_n(t)}{dt}.\frac{r_n(t)}{r_n(t)} = \lambda_1(t).r_1(t).r_2(t)...r_n(t) + r_1(t).\lambda_2(t).r_2(t)...r_n(t) + ... +$$

$$+ r_1(t).r_2(t)...r_n(t).\lambda_n(t) = R(t).(\lambda_1(t) + \lambda_2(t) + ... + \lambda_n(t)) = R(t)\sum_{i=1}^{n}\lambda_i(t) \qquad (3)$$

Failure intensity in series system

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{R(t)\sum_{i=1}^{n}\lambda_i(t)}{R(t)} = \sum_{i=1}^{n}\lambda_i(t) \qquad (4)$$

The resulting reliability of the series system is always less value than the reliability of the most unreliable component from the given system (Figure 2).

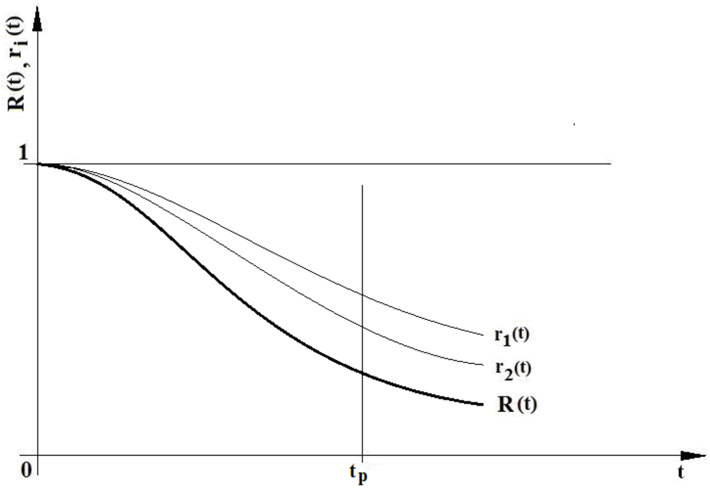

Fig. 2. Time behaviour of the reliability of the system and components in the case of series interconnection

2.2. Parallel systems

Parallel interconnection is a configuration of components in the reliability block diagram, in which a system failure occurs when all components fail. A reliability block diagram for parallel systems is shown in Figure 3. Reliability indicators for parallel systems are calculated by using the following formulas:

Probability of failure in parallel systems

$$F(t) = (1 - r_1(t)).(1 - r_2(t))...(1 - r_n(t)) = \prod_{i=1}^{n}(1 - r_i(t)) \qquad (5)$$

Probability of a failure-free operation in parallel systems

$$R(t) = 1 - F(t) = 1 - \prod_{i=1}^{n}(1 - r_i(t)) \qquad (6)$$

Failure probability density in parallel systems

$$f(t)=\frac{dF(t)}{dt}=\frac{d(1-r_1(t))}{dt}.(1-r_2(t))\ \dots\ (1-r_n(t))\ +\ (1-r_1(t)).\ \frac{d(1-r_2(t))}{dt}\ .\ (1-r_3(t))\ \dots\ r_n(t)\ +\ \dots\ +$$

$$+\ (1-r_1(t)).(1-r_2(t))\ \dots\ (1-r_{n-1}(t)).\ \frac{d(1-r_n(t))}{dt}$$

Each element is expanded by quantity $\frac{(1-r_i(t))}{(1-r_i(t))}$, for i = 1, 2, ..., n. Then:

$$f(t)=\frac{d(1-r_1(t))}{dt}.\frac{(1-r_1(t))}{(1-r_1(t))}.(1-r_2(t))\dots(1-r_n(t))$$

$$+(1-r_1(t)).\frac{d(1-r_2(t))}{dt}.\frac{(1-r_2(t))}{(1-r_2(t))}.(1-r_3(t))\dots(1-r_n(t))+\dots+$$

$$+(1-r_1(t)).(1-r_2(t))\dots(1-r_{n-1}(t)).\frac{d(1-r_n(t))}{dt}.\frac{(1-r_n(t))}{(1-r_n(t))}=$$

$$=\frac{d(1-r_1(t))}{dt}.\frac{1}{(1-r_1(t))}.(1-r_1(t)).(1-r_2(t))\dots(1-r_n(t))+$$

$$+(1-r_1(t)).\frac{d(1-r_2(t))}{dt}.\frac{1}{(1-r_2(t))}.(1-r_2(t)).(1-r_3(t))\dots(1-r_n(t))+\dots+$$

$$+(1-r_1(t)).(1-r_2(t))\dots(1-r_{n-1}(t)).\frac{d(1-r_n(t))}{dt}.\frac{1}{(1-r_n(t))}.(1-r_n(t))=$$

$$=F(t).\sum_{i=1}^{n}\frac{d(1-r_i(t))}{dt}.\frac{1}{(1-r_i(t))}=(1-R(t))\sum_{i=1}^{n}\frac{d(1-r_i(t))}{dt}.\frac{1}{(1-r_i(t))} \tag{7}$$

Failure intensity in parallel systems

$$\lambda(t)=\frac{f(t)}{R(t)}=\frac{(1-R(t))}{R(t)}\sum_{i=1}^{n}\frac{d(1-r_i(t))}{dt}.\frac{1}{(1-r_i(t))} \tag{8}$$

The resulting reliability of the parallel system is always higher than the reliability of the most reliable component from the given system (Figure 4).

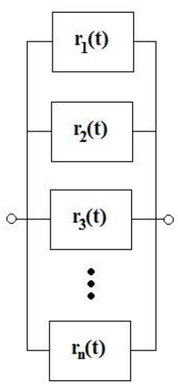

Fig. 3. Reliability block diagram of parallel interconnection

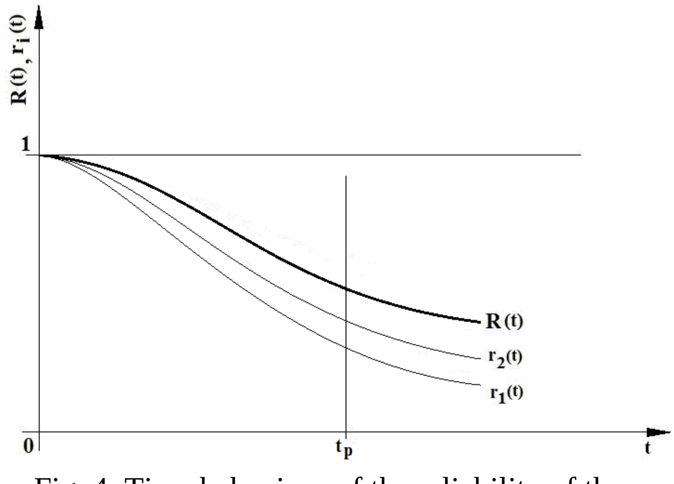

Fig. 4. Time behaviour of the reliability of the system and components in the case of parallel interconnection

2.3. Combined systems

Combined systems merge series and parallel subsystems into a single system. A combined interconnection diagram is shown in Figure 5.

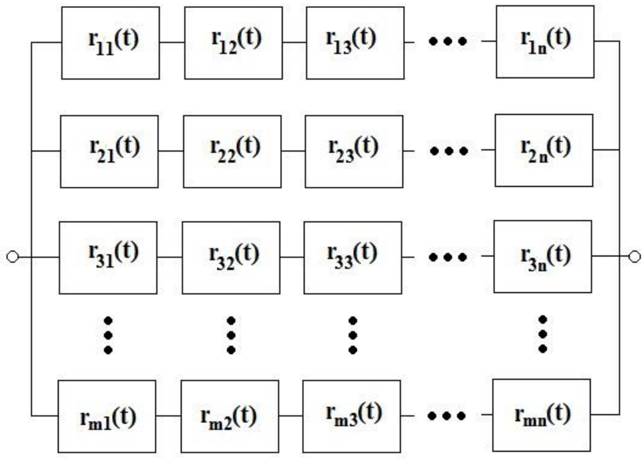

Fig. 5. Reliability block diagram of a combined interconnection

Reliability indicators for combined systems are calculated by using the following formulas:

Probability of a failure-free operation in combined systems

$$R(t) = 1 - (1 - r_{11}(t).r_{12}(t)...r_{1n}(t)) \,.\, (1 - r_{21}(t).r_{22}(t)...r_{2n}(t)) \,...\, (1 - r_{m1}(t).r_{m2}(t)...r_{mn}(t)) =$$
$$= 1 - \prod_{i=1}^{m} (1 - \prod_{j=1}^{n} r_{ij}(t)) \tag{9}$$

where: $i = 1, 2, ..., m$ (number of branches in the system); and $j = 1, 2, ..., n$ (number of components in the branches of the system).

Probability of failure in combined systems

$$F(t) = 1 - R(t) \tag{10}$$

Failure probability density in combined systems

$$f(t) = \frac{dF(t)}{dt} \tag{11}$$

Failure intensity in combined systems

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{12}$$

3. RESULTS OF RELIABILITY EVALUATION FOR THE MAIN STRUCTURAL VARIANTS OF A LIFTING MECHANISM

This chapter presents a reliability analysis of five solution variants for lifting mechanisms in bridge cranes.

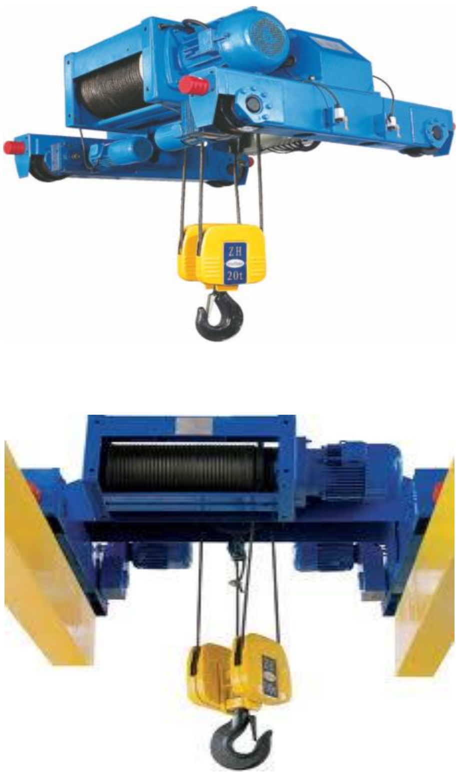

Fig. 6. Examples of crane lifting mechanism (Demag Cranes)

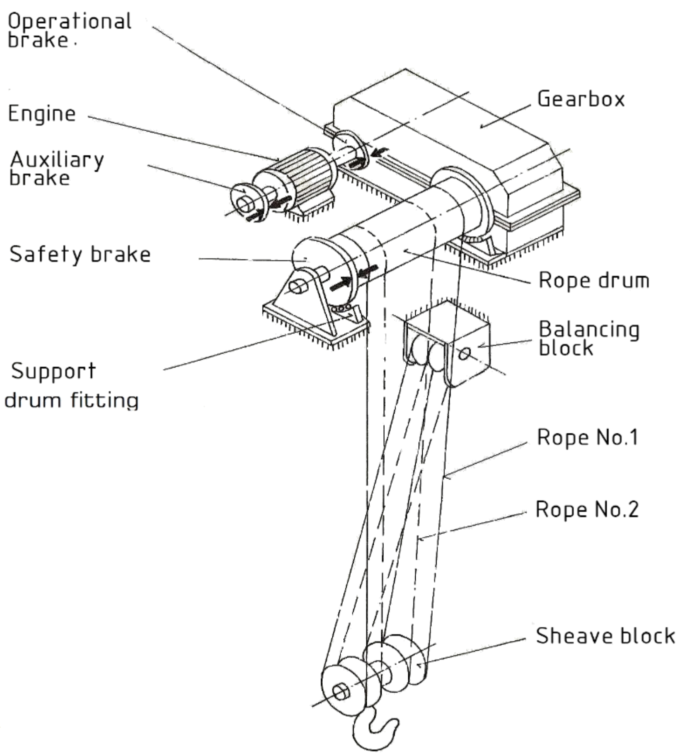

Fig. 7. Scheme of crane lifting mechanism

The first variant (ZM A) represents the most complex configuration of the lifting mechanisms, whose modification through structural simplifications creates the other four variants (ZM B to ZM E).

Figure 6 illustrates typical structural solutions for lifting mechanisms in bridge cranes. Figure 7 shows a scheme for a lifting mechanism in its most complex structural configuration (ZM A).

Table 1 presents an overview of structural solutions for all five variants of lifting mechanisms, i.e., from ZM A to ZM E.

The next section presents the results of an investigation into the extent to which the probability of a load drop event can be affected by structural simplifications. For this purpose, it is necessary to configure reliability block diagrams for each variant of the lifting mechanism. (Figure 8).

Table 1. Overview of design differences among the individual variants from ZM A to ZM E

Variant ZM	Description
ZM A	Lifting mechanism matches the illustration in Figure 7
ZM B	Like ZM A, but without a support drum fitting, and with a single rope
ZM C	Like ZM B, but without an auxiliary brake
ZM D	Like ZM B, but without a safety brake
ZM E	Like ZM C, but without a safety brake

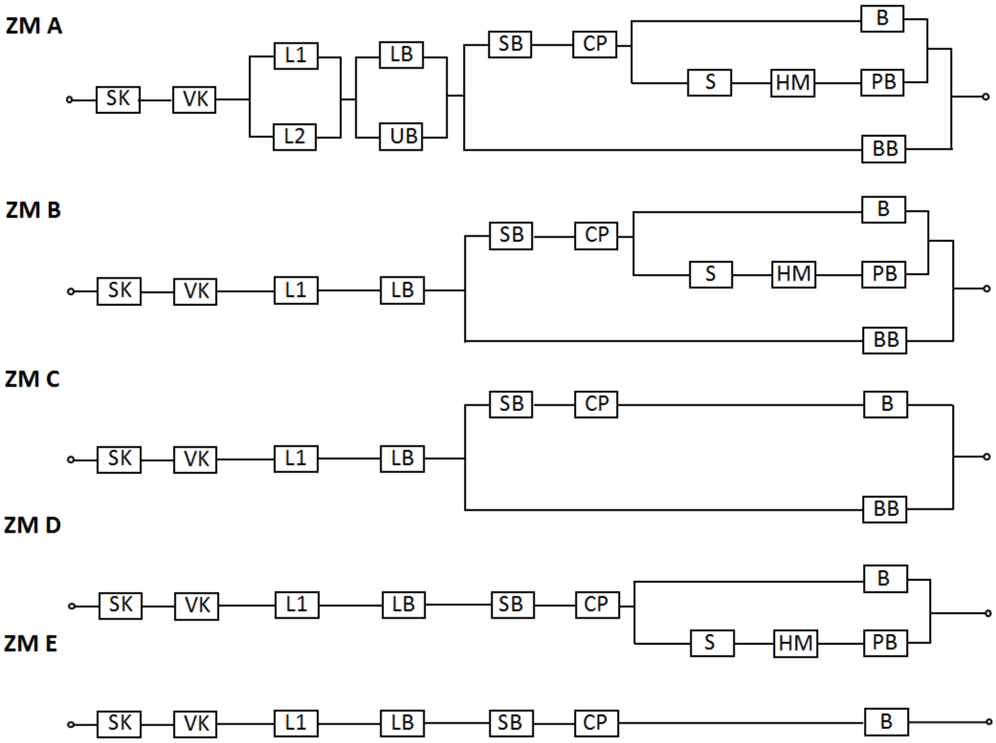

Fig. 8. Reliability block diagrams of lifting mechanism variants

The designated symbols in the reliability block diagrams for the individual components of the lifting mechanism refer to the following:

SK – sheave block with a lifting hook
L – rope
VK – balancing block
LB – rope drum including support fitting
UB – support drum fitting
SB – drum clutch
CP – front gearbox
S – clutch
HM – motor shaft including support fitting
BB – safety brake
PB – auxiliary brake
B – operational brake

A load drop event, i.e., lifting mechanism failure, does not occur if:

- The sheave block (SK) or the balancing block does not incur damage (VK)

- One of the two ropes is intact
- The rope drum, including its support fitting or the support fitting (UB), is intact
- The rope drum remains locked

The rope drum remains locked if the safety brake (BB) is functional, or if the drum clutch (SB) and the gearbox (CP) transmit the braking torque from the drive. Weibull distribution, in its following analytical form, was used to describe the failure of the components in the analysed lifting mechanisms:

$$F(t) = 1 - e^{-\frac{(t-t_0)^b}{(a-t_0)}} \qquad (13)$$

It is characterized by parameters *a* (scale parameter), *b* (shape parameter) and t_0 .

The specified distribution is a suitable failure-free time or life model for machines or equipment that are affected by fatigue damage. To calculate the probability of failure $F(t)$ according to Weibull distribution, it is necessary to know the values of its parameters. The parameters were identified during life tests for the lifting mechanism shafts and their values were derived from [25]:

t_0 = 1,905,802 (number of loading cycles)
a = 4,567,187 (number of loading cycles)
b = 0.725

The *F(t)* function, which conveys the probability of failure, or alternatively, the probability of a load drop event for each of the five variants of lifting mechanisms (ZM A to ZM E), is shown in its dynamic graphical representation in Figure 9.

The calculation and drawing of the dynamic outcomes were acquired by using ASMBOOL, the software product specifically designed for this purpose.

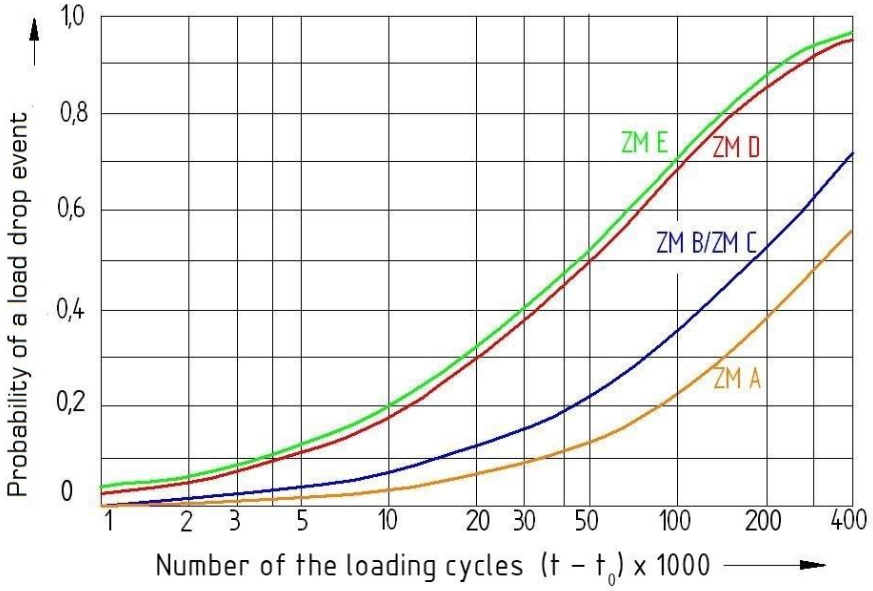

Fig. 9. Probability of a load drop event for the individual variants of lifting mechanisms, i.e., ZM A to ZM E

4. DISCUSSION

This article presents the findings of our investigation into the reliability of technical systems (more specifically, lifting mechanisms in bridge cranes) by calculating the probability of system failure, i.e., the probability of a load drop event for five variant designs of the analysed mechanisms.

Figure 9 illustrates three groups of dynamic curves for the probability of a load drop event, namely, ZM E/D, ZM C/B and ZM A, which differ in the gradient of the increasing values of probability.

The ZM A variant appears to best suit the criteria of reliability and safety, since the probability of a load drop event in this case developed at the slowest rate, and reached the lowest values for all other outcomes. In the real world, this would be caused by the fact that the ZM A mechanism features the most alternate safety components, i.e., brakes.

The dynamic outcomes for ZM B and ZM C overlap. This conjunction can be explained by the fact that a safety brake reduces the probability of a load drop event in both variants. The parallel configuration of an auxiliary brake, coupled with a motor shaft and a clutch, in comparison with the auxiliary brake, seems to have practically no effect on the probability of a load drop event.

The difference between the ZM A variant and the ZM B/C variants has ensued from using an extra rope and a support drum fitting in the former.

The most dramatic increase in the probability values of a load drop event is evident in the ZM D and ZM E variants. These configurations are therefore the least desirable to use. The minor difference between the two variants follows from using the safety brake feature in the ZM D configuration.

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