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Determinación de dependencia estadística de la temperatura de trabajo de rodamientos rígidos en procesos industriales mediante ANOVA en RStudio

Determination of statistical dependence of the working temperature of rigid bearings in industrial processes using ANOVA in RStudio

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Palabras claves: Densidad, lubricante, rodamiento, temperatura, velocidad.

Resumen

Introducción: Hoy en día la temperatura de trabajo se ha convertido en la variable más importante en la evaluación técnica del rendimiento general de un rodamiento rígido. Esto se debe principalmente a que varios factores críticos tienen una mayor o menor dependencia de la temperatura de trabajo, factores de funcionamiento como la viscosidad del lubricante, la capacidad de carga, la distribución de la carga y la pérdida de potencia que en distintas investigaciones se ha demostrado una proporcionalidad. **Objetivo:** En este artículo se determina la dependencia de la temperatura de trabajo de un rodamiento rígido de bolas 618 en función de variables operativas como la densidad de película lubricante y velocidad de funcionamiento al que está expuesto este elemento dentro del proceso industrial de trituración de minerales. **Resultados:** Se realizaron 27 mediciones in situ de la temperatura de trabajo a velocidades operaciones entre 1200 y 3600 revoluciones por minuto y densidades de lubricantes entre 100 y 135 centistokes. Estos datos obtenidos fueron procesados mediante ANOVA multifactorial para establecer la influencia de las variables antes expuestas en relación con la temperatura de trabajo, como resultado se pudo establecer que la velocidad de funcionamiento influye de forma directa sobre la variación de temperatura de trabajo del rodamiento rígido de bolas en estudio, lo que implica que esta variable debe ser analizada cuando se reemplace o dimensione el rodamiento. **Conclusiones:** Se concluyó que la temperatura de trabajo tiene una dependencia directa con la velocidad de funcionamiento del rodamiento en estudio y con el tipo de lubricante utilizado en el mismo, además se pudo determinar que el presente estudio aporta significativamente en la ejecución de tareas de mantenimiento, en la elaboración de planes de producción y en el análisis causa raíz de fallas en activos con elementos rotarios bajo contextos operacionales con distintas variables de funcionamiento a nivel industrial. **Área de estudio general:** Ingeniería. **Área de estudio específica:** Ingeniería Industrial.

Keywords: Density, lubricant, bearing,

Abstract

Introduction: Nowadays the operating temperature has become the most important variable in the technical evaluation of the overall performance of a deep groove bearing. This is mainly since

temperature, speed.

several critical factors have a greater or lesser dependence on the working temperature, operating factors such as lubricant viscosity, load carrying capacity, load distribution and power loss, which have been shown to be proportional in various investigations. Objective: In this article, the dependence of the working temperature of a 618 deep groove ball bearing on operating variables such as lubricant film density and operating speed to which this element is exposed in the industrial process of mineral crushing is determined. Results: 27 in situ measurements of the working temperature were carried out at operating speeds between 1200 and 3600 revolutions per minute and lubricant densities between 100 and 135 centistokes. These data obtained were processed by means of multifactorial ANOVA to establish the influence of the above-mentioned variables in relation to the working temperature. As a result, it was established that the operating speed has a direct influence on the variation of the working temperature of the deep groove ball bearing under study, which implies that this variable should be analyzed when the bearing is replaced or sized. Conclusions: It was concluded that the working temperature has a direct dependence with the operating speed of the bearing under study and with the type of lubricant used in it, in addition it could be determined that the present study contributes significantly in the execution of maintenance tasks , in the elaboration of production plans and in the root cause analysis of failures in assets with rotating elements under operational contexts with different operating variables at industrial level.

Introduction

Thermal analysis of bearings is a topic that has been investigated for several years, where estimating the temperature of ball bearing components has great significance. According to Takabi & Khonsari (2013), "by applying the basic laws of heat transfer to the bearing assembly and using the assumption of lumped mass, the steady-state temperature of the bearing components can be estimated" (p. 94). For the reasons mentioned above, several researchers have dedicated themselves to developing methodologies capable of generating predictions of the bearing's working temperature.

Nowadays, the different industrial processes have become the fundamental pillar of the productive sector. Their purpose is to produce different products, always seeking to achieve the highest quality standards and so that the company is competitive in the market and does not disappear in the short term. In order to obtain these indicators, it is necessary to develop permanent technical follow-ups of the different variables inherent to the operational context and which are emitted by the machines that make up the industrial process involved, and that a change in them is an indication of possible failures, which if not treated in time would lead to a state of breakdown of the asset, thereby causing losses to the organization. Periodic monitoring is much more profitable than an unforeseen stoppage of a machine, equipment or installation.

Rotating machines are part of every production process, so to achieve improvements in the process we must monitor the variables of these machines and discover the interrelation that exists in the appearance of each of them. In the different rotating machines, bearings are the most common mechanical elements that we can find, so monitoring the variables in real time requires greater care. "Because they allow appropriate technical evaluations to be carried out, this is because the analog variables that they emit when the bearings are in operation give a clear idea of the state in which they are found, as well as the diagnosis of the faults that occur in their components" (Estévez & Bernal, 2019, p. 86). Therefore, the above-mentioned become the foundation for the present study.

Analog variables such as working temperature can determine hidden faults in the optimal functioning of bearings, taking these elements as a priority because if they fail they can cause unforeseen stops that undoubtedly reduce the production and maintenance rates desired in any organization, so determining the appropriate method for the analysis of the interrelation of the possible causes that generate alterations in the working temperature is essential, since it allows for timely technical actions to be carried out that guarantee the preservation of the required function of this mechanical element.

It should be noted that the analysis of the lubricating film was also based on the life cycle analysis of the lubricating grease, due to the impact it has both on the environmental order and on the influence on the operation of the bearing, it is important to identify advantages and disadvantages, as well as different strategies that allow minimizing the possibility of eventual risks. According to Ji et al. (2023), "the maximum temperature caused by a lubricating film is one of the key indicators to determine if the main equipment is functioning normally" (p. 57). Therefore, a prior analysis of the lubrication process is important to determine its impact on the proper functioning of the bearing in question.

This paper develops a methodology capable of analyzing the data emitted by temperature as a dependent variable, through statistical models to observe the interaction that exists between independent variables such as the revolutions per minute of operation and the density of the lubricating grease used in the bearing, all this in order for the company where the study was developed to have optimal processes based on the lowest variability. Therefore, it uses the analysis of variance as a statistical tool to be able to treat the data obtained, an analysis of variance using ANOVA is carried out, to determine if any controllable factor or any interaction between factors has a significant influence on the temperature variable (López & Osorio, 2015).

In the industrial field, the implementation of change management in industrial processes has been practiced and disseminated, which has generated great competitive advantages. According to Oropesa & Martínez (2015), change management is the formal process to address organizational change, which includes a systematic approach and application of knowledge (p. 58). Therefore, this research also seeks to generate such management, given that an organizational change undoubtedly generates greater profitability for the organization, regardless of the class or sector in which it is developed, systematization and logically the application of knowledge play an important role in achieving results in the industrial sector. Where every management system must be progressive and always seek innovation.

Experimental analysis of heat generation in rolling bearings is a methodology that currently demonstrates great results in the technical evaluation of the thermal nodes of a rolling element and its interaction with the environment. According to Gao et al. (2023), "thermal nodes around deep groove ball bearings are established by the heat network method" (p. 34). Based on the above, it can be established that both the working speed and the lubricant used in the bearing directly influence the thermal nodes of a ball bearing, so these can have an important connotation in the experimental part.

Another indispensable variable in a rigid bearing is the roughness height, which undoubtedly significantly influences proper operation. According to Zhu et al. (2020), "as the dimensionless surface roughness height of the bearing and journal increases or the degree of misalignment increases, the maximum dimensionless film pressure, the dimensionless load capacity, and the dimensionless misalignment moment of the bearing increase" (p. 102). Based on the above, it can be determined that lubrication has factors that directly influence the proper technical behavior of a rolling element.

In rolling elements, surface texture plays a major role in evaluating the frictional operating temperature. According to Song et al. (2020), "surface texture is an effective method to solve this problem, especially the conventional texture shape and the new surface texture shape design of radial and thrust sliding bearings" (p. 58). This variable undoubtedly has great significance both in the design and in the real-time evaluation of radial and tangential sliding elements.

The variables taken into account in this research are based on the dynamic behavior of the bearings. According toXiang et al. (2020), "it is of great importance to study the dynamic behavior of bearings during start-up to optimize tribology performance and improve service life" (p. 61). Therefore, it is important to also analyze variables such as friction at start-up and the state of the lubricant after a work shift.

Currently, there are several statistical models that seek a comprehensive evaluation of the working conditions of a bearing, either by temperature or by lubricating oil. According to Shan et al. (2023), "the general method for establishing the dependence model of ball bearing lubrication analysis and the characteristics of the oil-air multiphase flow inside the ball bearing is revealed by ANOVA" (p. 34). From the above, it can be seen that the generated studies take into account the geometric characteristic of the element that introduces the microspace in the chamber in the simulation model and the complicated limiting shape of the ball bearing is developed.

A relatively new topic in the study of industrial processes is thermal management, which has allowed for a greater expectation of the influences of the variables surrounding the proper functioning of a rolling element in a production system. According to Kim et al. (2023), "proper thermal management of the bearing is extremely important, because a high temperature beyond its operating limit can degrade the properties of the material and the lubricant, causing an unexpected failure" (p. 91). That is why this research aims to investigate the thermal characteristics of a ball bearing and its dependence on the operating speed and the characterization of various lubricants.

Methodology

This study was carried out in a mining material treatment company located in the canton of Ambato, in the province of Tungurahua, it is a company that carries out the process of exploitation, treatment and transportation of mining material used in different processes at an industrial level, being one of the main supplier companies of raw material of a stone type in the country, reason why the study carried out was of great pleasure to the technical and administrative staff of the organization, since it was possible to demonstrate that with an adequate follow-up the company can generate a greater utility and with it guarantee the quality standards that it promulgates to its clients.

As stated by Hernández & Diaz (2018), in their article "EVALUATION OF AN INDUSTRIAL BIODIESEL PRODUCTION PROCESS THROUGH LIFE CYCLE ANALYSIS", it is important to analyze the performance of the current process of the production system, as well as the proposal that integrates tools such as the study of Life Cycle Analysis and multifactorial ANOVA that allow a true integration of knowledge through technical and statistical studies.

The lubricant film plays a very important role in evaluating the working temperature of a deep groove bearing. According to Rao et al. (2019), “a suitable calculation method could

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overcome the discontinuity of the oil film at the edge and describe the surface texture characteristic on the ring.” Thus, modeling and simulation are also attractive techniques to improve the lubrication performance of ball bearings and thus lead to better control of the working temperature in a rotating system, which is present in any industrial process.

The organization's production plants are distributed by production lines, each of which is in charge of a leader who is in charge of supervising the processes and carrying out technical interventions if necessary, in addition to notifying and complying with both the master production plan and the preventive maintenance plan that the company has. These two plans have undergone changes thanks to this study, since optimal maintenance frequencies have been generated through appropriate monitoring of the variables of the production process that were not taken into account at the time of designing said technical documentation.

In the crushing plant, in the pre-crushing section, 12 crushing machines are used, semi-automatic machines with mechanical and pneumatic systems, depending on the dimensions of the stone material, the crushing machines operate at different speeds, which causes different behavior of the process variables, the crushers have a set of grinding wheels capable of reducing the size of the stone material extracted from natural mines by alternating movement, this set is supported on shafts and to generate the movement it uses bearings with external diameters greater than 19 centimeters, therefore the failure of one of these elements would cause a stoppage in the crusher, and depending on the degree of affectation it can cause a prolonged period of unproductivity of the plant.

When analyzing the crushing process of the stone material, it can be identified that the variables viscosity of the lubricating grease and the working speed are directly related. According to Li et al. (2018), "it is experimentally demonstrated that the addition of lubricant could effectively increase the volumetric efficiency by 10.5% and the specific energy consumption of a SSC by 43.3%" (p. 138). That is why the first has centistokes as its unit of measurement and the second revolutions per minute, technically these two independent variables are the ones that probably cause the bearing temperature to be unstable, emphasizing that the bearing in question is numbered 618, which by design has a speed limit of 9500 revolutions per minute, and that in the operation of the compressor it is well below this limit, for lubrication two types of grease are used, which are the most appropriate for the asset.

Therefore, it is unknown whether the viscosity of the lubricating grease or the operating speed cause significant variations in the working temperature of the rolling element, which has caused it to deteriorate rapidly, causing unforeseen stoppages, which translate into losses for the company, not only due to the untreated stone material, but also other problems such as loss of customer confidence due to late product deliveries, in addition to low quality in the final stone product, due to a malfunction of the grinding wheel set.

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Therefore, it is necessary to apply an experimental design to identify which of the two variables causes the working temperature of the bearing to have different values, with multifactorial analysis being the ideal statistical tool for processing the data obtained in situ, in addition to the fact that said analysis can appropriately identify whether the variables treated have a direct influence on the working temperature of the element involved in the present study.

In the mining company, during the crushing process, unforeseen stoppages have occurred in the crushing machine, causing the entire process to stop. This is because the bearings of said machine suffer premature wear due to different variables, inherent to the process and which significantly affect the normal operation of the aforementioned asset, even breaking down on several occasions. Therefore, a technical follow-up is carried out at the working temperature, at different operating speeds and with different densities in the lubricating greases, since they are the technical variables that are directly related to the bearing and the temperature it generates when working under the established operational context. It should be noted that the measurements were carried out on-site and at equal time intervals, to guarantee the measurement, obtaining the following data:

Table 1

Working temperature of rigid bearing

	Operating Speed (rpm)			
	1200	1800	3600	
Density of Lubricating Grease used				
	73	93	94	
Lithium EP Grease (100 cSt)	80	89	98	
	76	91	101	
	88	92	87	Temperature
AR-16 Aluminum Grease (120 cSt)	84	106	96	Of
	93	88	105	Job
	81	96	92	°C
Asphalt Grease (135 cSt)	87	72	102	
	94	103	97	

*Note:*This table shows the measurements that were taken on site in a technical manner, in equal periods and under repeatability and reproducibility to ensure the reliability of the study.

Objective statement

Determine the dependence of the working speed of the deep groove ball bearing 18 on the variables of lubricating grease density and operating speed, considering α = 0.05.

Significance Hypothesis

H0= THERE IS NO DISTINCT PAIR

H1= AT LEAST ONE PAIR IS DIFFERENT

α= 0.05

Normality Hypothesis

H0= THE RESIDUALS FOLLOW A NORMAL DISTRIBUTION

H1= THE RESIDUALS DO NOT FOLLOW A NORMAL DISTRIBUTION

α= 0.05

Homoscedasticity Hypothesis

H0= THERE ARE NO DIFFERENCES BETWEEN THE VARIANCES

H1= THERE ARE DIFFERENCES BETWEEN THE VARIANCES

α= 0.05

Results

In this research we start from the analysis of variances, for which we reorder the data, in such a way that they can be treated statistically in the R Studio program, in order to demonstrate that the developed methodology can be repeated and reproduced in another element, thus guaranteeing that the present study can be applied in different assets, in different elements and in different production processes.

Then, the variables were factor transformed and ANOVA was applied.

TRANSFORM TO FACTOR AND THEN APPLY ANOVA

Speed=factor (Speed)

Density=factor (Density)

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Later we created an "aovdata" object that contains TWO-FACTOR ANOVA for the analysis of the aforementioned variables.

aovdata=aov(Temperature~Speed+Density+Speed*Density)

Obtaining the following results in this way:

summary(aovdata)

Figure 1

Factor transformation of the study variables

```
# TRANSFORMAS A FACTOR Y LUEGO APLICAR ANOVA
Velocidad=factor(Velocidad)
Densidad=factor(Densidad)
aovdata=aov(Temperatura~Velocidad+Densidad+Velocidad*Densidad)
summary(aovdata)

> summary(aovdata)
                   Df Sum Sq Mean Sq F value  Pr(>F)
Velocidad           2  766.5   383.3   6.260 0.00863 **
Densidad            2  111.2    55.6   0.908 0.42101
Velocidad:Densidad  4  203.3    50.8   0.830 0.52342
Residuals          18 1102.0    61.2
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

For hypothesis testing, we analyze the SIGNIFICANCE:

The significance of the SPEED effect

Figure 2

Significance analysis of the variable Speed

```
> summary(aovdata)
                   Df Sum Sq Mean Sq F value  Pr(>F)
Velocidad           2  766.5   383.3   6.260 0.00863 **
Densidad            2  111.2    55.6   0.908 0.42101
Velocidad:Densidad  4  203.3    50.8   0.830 0.52342
Residuals          18 1102.0    61.2
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

The p-value for SPEED is 0.00863 is below the threshold 0.05, therefore, reject H0.

It means that one or more pairs of those results that have been obtained in terms of SPEED are significant. Therefore, SPEED is significant.

The significance of the DENSITY effect

Figure 3

Analysis of the significance of the Density factor.

```
> summary(aovdata)
                   Df Sum Sq Mean Sq F value  Pr(>F)
Velocidad           2  766.5   383.3   6.260 0.00863 **
Densidad            2  111.2    55.6   0.908 0.42101
Velocidad:Densidad  4  203.3    50.8   0.830 0.52342
Residuals          18 1102.0    61.2
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

The p-value for DENSITY is 0.42101 is above the threshold 0.05, therefore, I accept H0. It means that DENSITY is not significant.

The significance of the interaction SPEED vs. DENSITY

Figure 4

*Analysis of the*significance of the interaction SPEED vs. DENSITY

```
> summary(aovdata)
                   Df Sum Sq Mean Sq F value  Pr(>F)
Velocidad           2  766.5   383.3   6.260 0.00863 **
Densidad            2  111.2    55.6   0.908 0.42101
Velocidad:Densidad  4  203.3    50.8   0.830 0.52342
Residuals          18 1102.0    61.2
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

The p-value for interaction is 0.52342 is above the threshold 0.05, therefore I accept H0. It means the interaction is not significant.

To check the reliability of the results, we verify whether it meets the assumptions, starting with the NORMALITY test:

Since there is little data, we used the Shapiro test,

Figure 5

Normality function of residuals

```
#NORMALIDAD DE LOS RESIDUALES
shapiro.test(aovdata$residuals)
```

The significance of the interaction SPEED vs. DENSITY

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Figure 6

*p - Value*of the residuals.

```
        Shapiro-Wilk normality test

data:  aovdata$residuals
W = 0.96953, p-value = 0.5894
```

The p-value of the residuals is 0.5894 which is above the threshold 0.05, therefore I accept H0.

It means that the residuals would follow a Normal Distribution.

Homoscedasticity is verified by Levene's test:

Figure 7

Homoscedasticity TEMPERATURE vs. SPEED

```
#VERIFICACION DE HOMO
library(lawstat)
levene.test(Temperatura,Velocidad)
levene.test(Temperatura,Densidad)
```

Homoscedasticity TEMPERATURE versus SPEED

Figure 8

p – TEMPERATURE value vs. SPEED

```
> levene.test(Temperatura,Velocidad)

        Modified robust Brown-Forsythe Levene-type test based on the absolute
        deviations from the median

data:  Temperatura
Test Statistic = 0.52822, p-value = 0.5964
```

The p-value of TEMPERATURE against SPEED is 0.5964 is above the threshold 0.05, hence I accept H0.

It means that there is homogeneity of variances TEMPERATURE against SPEED.

Homoscedasticity TEMPERATURE versus DENSITY

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Figure 9

p – TEMPERATURE value vs. DENSITY

```
> levene.test(Temperatura,Densidad)

        Modified robust Brown-Forsythe Levene-type test based on the absolute
        deviations from the median

data:  Temperatura
Test Statistic = 0.19806, p-value = 0.8216
```

The p-value of TEMPERATURE versus DENSITY is 0.8216 is above the threshold 0.05, hence I accept H0.

It means that there is homogeneity of variances TEMPERATURE versus DENSITY.

Discussion

For the discussion of this research, the interaction graph was developed

To generate the graph we use the code:

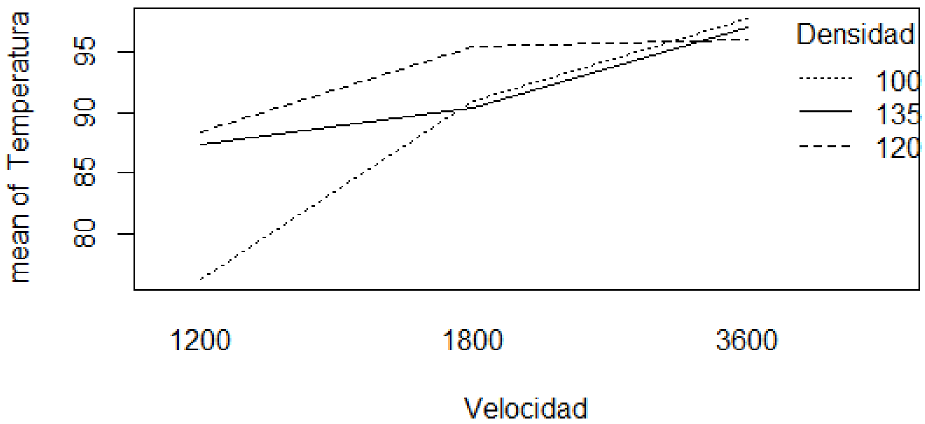
#WE MADE INTERACTION GRAPHIC

interaction.plot(Velocity,Density,Temperature,main="Interaction plot")

Obtaining the Interaction Graph shown below:

Figure 10

Interaction graph



From the results described in the previous point, we can establish that:

- ONLY SPEED influences the change in the operating temperature of the bearing.
- DENSITY does not influence the change in the operating temperature of the bearing.
- THE INTERACTION between the two variables does not influence the change in the working temperature of the bearing.
- It was determined that the residuals follow a Normal Distribution.
- There is homogeneity of variances TEMPERATURE against SPEED.
- There is homogeneity of variances TEMPERATURE versus DENSITY.
- In the graph we can establish that the three curves have a certain graphic similarity, they have the same shape, graphically there is no interaction, that is, there is no significance in the interaction, that is, the interaction has no influence.
- Compiling all the results we can establish that it is feasible to analyze the working temperature in deep groove ball bearings using Two-Way Analysis of Variance.

Conclusions

- Once the ANOVA method for two factors has been analyzed, it can be concluded that it is a tool that allows us to reliably determine whether a phenomenon or condition is the result of the influence of one or more variables, in this case the dependence of the working temperature on the speed of the industrial process and the lubricant used.
- After having carried out the experimental work, it can be concluded that for the case under study, speed is the independent variable that influences the working temperature of the bearing, based on the fact that the residuals are normal and that there is Homoscedasticity between factors and response, thus achieving the objective of this research.
- It can be concluded that ANOVA can be applied to statistically establish the dependence of any variable, in this case of an industrial process, and that it contributes significantly to the potentialization of a productive system, to the point of being a tool in decision-making such as the purchase of a lubricant or the optimal control of the speed of a machine.
- Finally, with the use of the R Software we can conclude that even graphically we can determine the influence that two or more independent variables have on a dependent variable, which undoubtedly clarifies the panorama of the dependence of variables, regardless of their type, making the present study reproducible and replicable.

Conflict of interest

The authors declare that there is no conflict of interest in relation to the submitted article.

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