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Analysis of the loading process effect on the tribological node geometry change of agricultural machine

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Abstract

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The effect of loading on the properties of selected sliding pairs has been analysed. The experimental tests were performed using the testing machine Tribotestor M10. The steel 11 600 and all-bronze sleeve of CuSn12 material has been selected as the elements of friction pair. Two oils were selected for lubrication of friction node – the mineral gear oil Madit PP80 and ecological oil Plantohyd 46 S. Chosen friction pairs were tested in three loading regimes (two dynamic processes and one static process). 60 tribological tests have been performed. The weight loss, the change of surface roughness and the absolute change of cylindricity of the friction pair elements were the tracked and analysed parameters. Based on the experiments, various effects of loading regimes may be concluded. The obtained results confirmed that the power spectral density of generated signal is probably an important criterion for assessment in terms of simulated random dynamic load in the given experiment. From the technical perspective, the power spectral density is actually the amount of energy supplied to the process.

Keywords: tribotestor; random process; sliding node

Working conditions of agricultural machinery are so heterogeneous and specific that they very adversely affect the life of individual components and nodes. The vast majority of agricultural machinery in operation is exposed to dynamic effects. The stress of structural parts caused by adverse operating load crucially determines their operational reliability. New approaches to designing structures require these characteristics of operating load to be respected and included in the calculation and construction procedures and taken into account when designing new machinery and equipment. Reliable operation of agricultural machinery, however, generally depends on the reliability of tribological node. It is a place where functional parts of the node interact, while external and internal factors are in action (Kučera, Pršan 2008; Kučera et al. 2014).

The result of adverse operating load on the tribological node in operation is their wear and thus an increase of clearance of the friction pair. Practice shows that the most common cause of decommissioning of shafts is the loss of their functional capacity due to wear (Kučera, Rusnák 2008).

In simulated tribological tests, efforts have been made to simulate the tribological behaviour of the practical system or its part through model tests. This implies that the area of tribometry is extremely difficult, due to the complexity of tribological processes and a large number of influencing factors (Bayer 2004; Stachowiak, Batchelor 2014). The use of the systems approach is extremely im-

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portant here. To fulfil these conditions, usually materials, lubricants and atmospheric environment are selected first. Further, geometric and contact conditions of the test system are adapted to conditions of a practical system, taking into account the question of the scale factor. Finally, operating variables are adjusted in order to obtain the same tribological interactions in both test and practical systems (Blaškovič et al. 1990; Czichos, Habig 2003).

Sensitive area of each node is its lubrication. This is particularly important from the perspective of environmental protection. One of the ways to fulfil this requirement is replacement of mineral and synthetic lubricants with environmentally friendly lubricants that are biodegradable (Schneider 2006; Kosiba et al. 2013; Tóth et al. 2014).

From the perspective of the possibility of application of environmentally friendly oils for lubrication of tribological nodes, the interesting results of tribological experiments are those where these oils were used and at the same time compared to the mineral oil or other environmentally friendly oil (even to each other). Based on the results of the experiment, the eco-friendly oil Arnica 46 S was comparable with the oil Madit PP 80 in the "pin-shaft" tests (Kročko 2012). Comparing the environmental oil of the producers Panolin, Fuchs and MOL with the Arnica oil, it was found that the results in conditions of the "pin-shaft" experiment are even better (Gáspár 2011). In conditions of the "pin-shaft" experiment with the oils Mogul, Plantohyd, Hydros and Naturelle of the same viscosity class 46, their order was determined based on the results of the experiments (Tóth et al. 2014). The oil PP80 and ecological oils Hydros UNI and Plantohyd 46 S were studied in dynamic stress conditions. In conditions of the given experiment, ecological oils had better results (Kostoláni 2013; Kučera 2014). The results of the mentioned experiments pointed to the need to examine the properties of organic oils due to the possibility of their application as substitutes for mineral or synthetic oils.

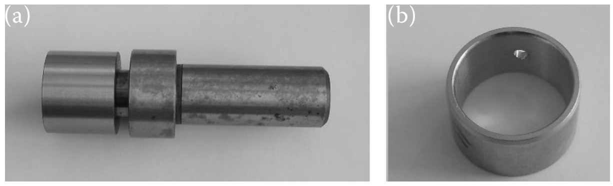

Fig. 1. View of the test sample of shaft type (a) and sleeve (b)

MATERIAL AND METHODS

A simple sliding node consisting of a shaft and sliding bearing for the purpose of the experiment was simulated. This represented the "pin-shaft" type of test with a line touch of friction node elements in the given experiment. Great attention was paid to the selection of suitable material. The steel 11 600 (EU – E355) was selected as the sample material for the shaft as it belongs to commonly used materials in manufacturing agricultural components of shaft type or pin type in various agricultural machines without heat treatment (tractors, harvesters, cutters, etc.), which have worn functional surfaces of cylindrical shape (Kučera 2014). The steel E355 is unalloyed construction steel suitable for machine components loaded statically and dynamically.

Even before grinding to final dimension the sample was pressed on an auxiliary shaft. The shafts were then grinded to the final dimension of Ø 29.960 mm to achieve the H8/f7 fit, i.e. the close clearance fit

Table 1. Deviation change of cylindricity of sleeves

Oil type	PP 80			Plantohyd 46 S		
Loading regime	ST	D1	D2	ST	D1	D2
Sleeves						
ΔC_1 before test (μm)	15.5	15.6	12.8	14.6	11.9	12.4
ΔC_2 after test (μm)	38.7	50.2	64.3	23.9	25.7	31.9
Change of cylindricity ΔC (μm)	23.2	34.3	51.5	9.4	13.7	19.4
Chafts						
ΔC_1 before test (μm)	8.5	6.2	6.1	5.2	6.0	6.3
ΔC_2 after test (μm)	9.9	8.0	7.6	6.3	9.3	9.7
Change of cylindricity ΔC (μm)	0.9	1.7	1.5	1.1	3.3	3.1

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Fig. 2. The experimental testing device Tribotestor M10

(Bhushan 2001; Shigley et al. 2010). The sample prepared in this way (as the first friction element) has undergone the experiment and subsequent assessment (Fig. 1a).

The sleeve was selected as the second friction element. The commercial marking of the sleeve is B60 and its dimensions are Ø 35r7 × Ø 30F7 × 20 (Fig. 1b). It is a centrifugally cast all-bronze sleeve from the material CuSn12. The material CuSn12 is tin bronze and it is used for manufacturing of slide bearings. The material is suitable for working conditions with hydrodynamic and limited lubrication as well as for transmission of rotating and sliding motion.

Tribological experiments were performed using the laboratory experimental testing device Tribotestor M10 (SUA, Nitra, Slovak Republic), which is designed to fast detection of parameters and properties of slide bearings in general (both at static as well as at random dynamic loading). The experimental device is located in laboratories of the Department of Machine Design of the Slovak University of Agriculture in Nitra. The device enables performing basic tribological experiments. The control system of the device enables changing the load and its process (as one of the main parameters of the experiment). The picture of the experimental test device is shown in Fig. 2.

Test parameters:
- loading force 1: 500–1,500 N (dynamic regime D1), according to generated and statistically processed random signal 1; mean value 1,000 N
- loading force 2: 500–1,500 N (dynamic regime D2), according to generated and statistically processed random signal 2; mean value 1,000 N
- loading force 3: 1,000 N (static regime) – marked as ST;
- Shaft operating speed: 180 min^{-1}
- time of test/Running-up period: 60 min/5 min with a loading of 500 N
- lubrication method: gravity feed (cup in a height of 500 mm)
- used oils: Madit PP80 (Slovnaft, Bratislava, Slovak Republic), Plantohyd 46 S (Fuchs Europe Schmierstoffe GmbH, Mannheim, Germany)
- material of shaft/of counterpart: steel 11 600 (E355)/CuSn12.

Simulation of random loading processes for experimental needs. Two random processes using own software at the department were simulated. This was followed by statistical analysis and calculation of main characteristics in the correlation theory of random processes. Subsequently, a periodogram, power spectral density and correlation functions were determined. The statistical significance of the highest frequency and other frequencies after the application of the Fisher´s exact test

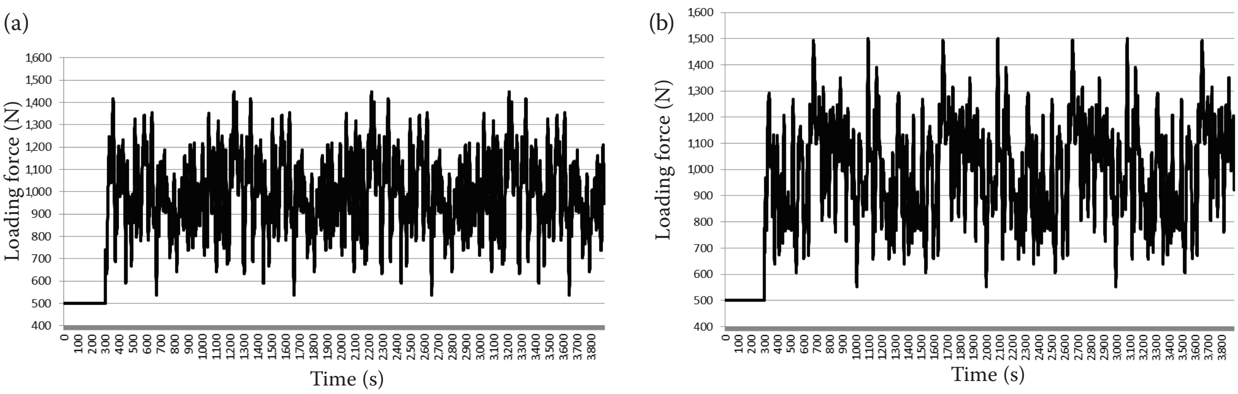

Fig. 3. Progress of force in dynamic loading, (a) signal No. 1 and (b) signal No. 2

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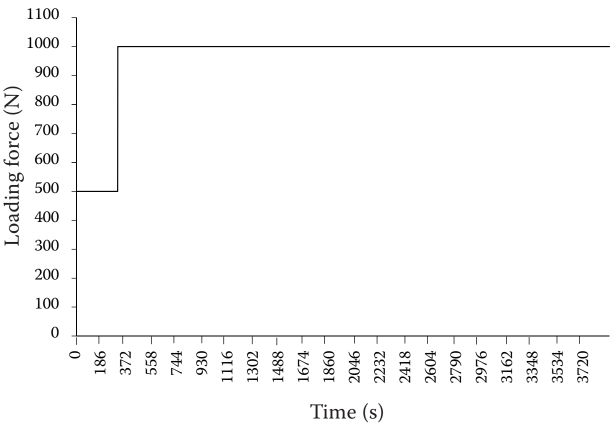

Fig. 4. Progress of force in static loading

were determinated. The most important frequency of the process No. 1 is 3.5296 Hz, and the most important frequency of the process No. 2 is 0.1008 Hz. The tests of stationarity showed that both processes are stationary (in mean value as well as in dispersion). Smoothed signals were used in loading as two dynamic regimes of loading with the mean value equal to the value of static loading (1,000 N). The progress of loading is shown in Figs 3–4.

The selected friction pairs were tested in three loading cycles and using two different lubricating oils according to the methodology. We performed 60 tribological tests in total, i.e. 10 for each loading regime and each lubrication methods. Each test started with the running-up period of 5 minutes. Equal conditions were set in this run-up period (in constant load) to achieve the stable state of friction of the friction pair. The measurement started automatically after the run-up period and was indicated by the control system. Each experiment was finished automatically after reaching the set time of test.

Wear (given by weight loss) is one of the most important characteristics of the behaviour of materials of friction pair under experimental conditions. The weight losses of materials using the laboratory scales Voyager® Pro (Ohaus Europe GmbH, Nänikon, Switzerland) with an accuracy of 0.001 g were detected. Weighing before and after the test was performed in stable conditions in order to minimize the measurement errors. The average values of weight loss of each material under experimental conditions were calculated from the measured data.

The change of surface roughness is another important parameter that characterizes the wear of friction node elements. Roughness *Ra* was the tracked and analysed parameter. The *Ra* value represents the mean arithmetic value of absolute deviations of the profile at *n* selected profiles for the basic length (ISO 4287:1997). The measurement was performed on the surfaces of both elements of friction node before and after the test, using the machine Mitutoyo SJ-201 (Mitutoyo Co., Kanagawa, Japan) with an accuracy of 0.002 μm.

The cylindricity of individual elements of the friction pair was measured using the machine MUK-F 300PC (Aquastyl Slovakia, s.r.o., Považská Bystrica, Slovak Republic) (accuracy of 0.1 μm) for all loading regimes and both oils before and after the experiment.

The results given in the figures and tables represent the mean values of 10 measured values for each parameter. The results of weight loss measurements and surface roughness changes were verified by ANOVA analysis. We tested the H_0 hypothesis – the equality of mean values of different loading (static ST, dynamic D1 and dynamic D2).

RESULTS AND DISCUSSION

The results of weight loss measurements are graphically presented in Fig. 5a (for sleeves) and in Fig. 5b (for shafts). The interpretation of results is quite clear in terms of the effect of loading regime on the size of wear under experimental conditions.

Based on the recorded and processed results of the experiment, the following can be stated:

– The smallest wear in the whole set of sleeve samples was observed at the static loading regime lubricated with the oil Plantohyd 46 S, and that was 0.0175 g. On the other hand, the highest size of wear was observed in sleeve samples loaded with the dynamic regime D2 and lubricated with the oil PP 80, and that was 0.0352 g. Dynamic loading regimes cause greater weight losses in comparison with static loading, regardless of the lubrication method. In terms of the oil used, it can be stated that the wear size of sleeves is smaller in samples lubricated with the ecological oil Plantohyd 46 S in comparison with the oil PP 80.
– ANOVA test result for weight loss of sleeves lubricated with oil Plantohyd 46 S showed that $Pr\ (> F) = 0.000489$ and we would therefore reject H_0 hypothesis for commonly used levels of significance (as $0.000489 < 0.10$; $0.000489 < 0.05$; $0.000489 < 0.01$). We may therefore de-

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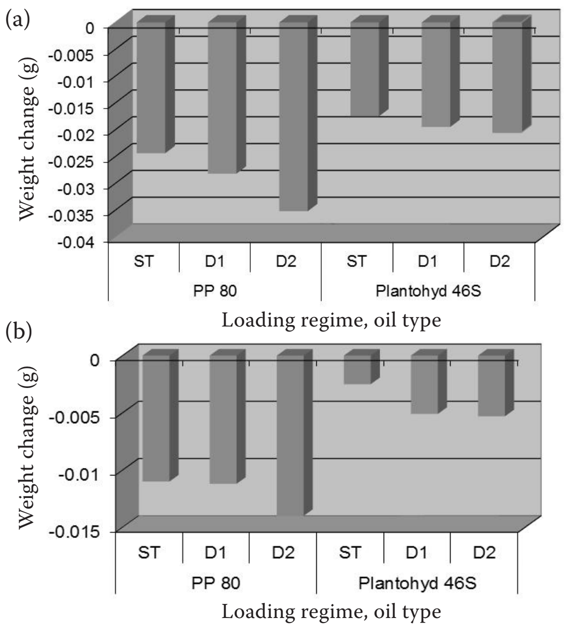

Fig. 5. Weight losses of (a) shaft and (b) sleeve

clare that differences between the effects of different loadings are statistically significant. Tukey's test confirmed that dynamic loading D2 had the greatest impact on the observed parameter. The mean values were: D1 = 0.0195, D2 = 0.0205, ST = 0.0175. Similar considerations apply to sleeves lubricated with oil Madit PP 80. *Pr* (> *F*) = 0.00050581 and therefore we would reject the H_0 hypothesis for commonly used levels of significance (as 0.00050581 < 0.10; 0.00050581 < 0.05; 0.00050581 < 0.01). We may therefore state that the differences between the effects of different loadings are statistically significant. The mean values: D1 = 0.0282, D2 = 0.0352, ST = 0.0244. Tukey's test also confirmed that dynamic loading D2 had the greatest impact on the observed parameter.

– The smallest wear in the whole set of shaft samples was again observed at the static loading regime lubricated with the oil Plantohyd 46 S, and that was 0.0025 g. The highest size of wear was observed in shaft samples loaded with the dynamic regime D2 and lubricated with the oil PP 80, and that was 0.014 g. In terms of the oil used, it can be stated (the same as for sleeves) that the wear size of shafts is smaller in samples lubricated with the ecological oil Plantohyd 46 S in comparison with the oil PP 80. In terms of loading regime, it can be stated that dynamic regimes cause greater weight losses in comparison with static loading, regardless of the lubrication method.
– Test results for the weight losses of shafts lubricated with oil Plantohyd 46 S:
  – the greatest loading – dynamic D2
  – the mean values: D1 = 0.0050, D2 = 0.0053, ST = 0.0025
  – D2 loading had the greatest effect to the observed parameter.
– Weight losses of shafts lubricated with oil Madit PP80:
  – the greatest loading – dynamic D2
  – the mean values: D1 = 0.0112, D2 = 0.0140, ST = 0.0110
  – D2 loading had the greatest effect to the observed parameter.

The results of surface roughness change *Ra* are graphically presented in Fig. 6. The results represent average values of recorded results for each loading regime.

Based on the results presented in Fig. 6, significantly greater changes of roughness *Ra* of sleeves (i.e. of softer material) can be stated in comparison with the shaft. We can also state a reduction of roughness in all tested sleeves (all regimes, both oils). The opposite situation was in shafts, where an increase of roughness was observed. These changes in shafts are very small in terms of absolute values. The effect of dynamic loading regimes, however, is significant. In terms of loading regime, its effect on the roughness change can be stated, the lubricating oil being irrelevant. The most significant change of roughness (reduction) was observed in sleeves loaded with the loading regime D1 and lubricated with the oil PP 80. The roughness parameter Ra was reduced by the amount 0.277 μm in this case.

The change of roughness parameter *Ra* in shafts was significantly lower compared to sleeves – an increase of roughness in all loading regimes was observed, regardless of the oil used. The most significant average change of roughness parameter *Ra* in shafts was recorded in the loading regime D2, an increase by the value of 0.051 μm.

– Test results of *Ra* change of sleeves lubricated with oil Plantohyd 46 S:
  – the greatest loading – dynamic D2
  – the mean values: D1 = 0.1000, D2 = 0.1100, ST = 0.0445
  – the D2 loading had the greatest effect to the observed parameter.

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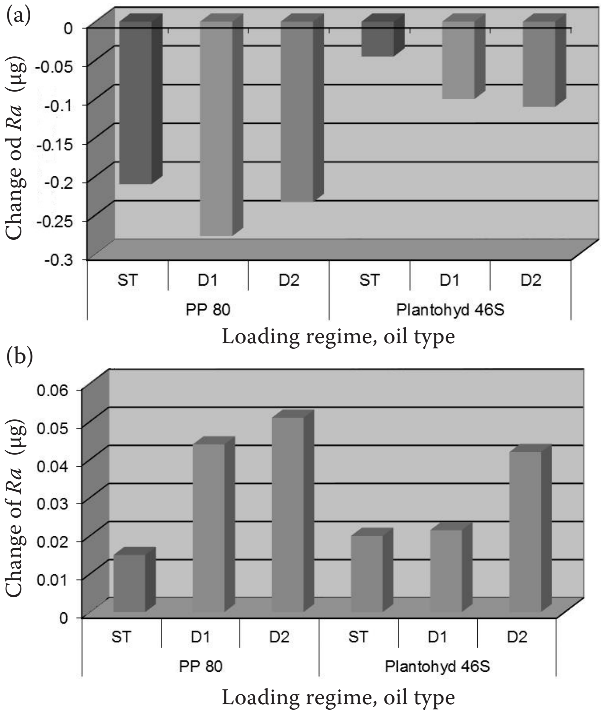

Fig. 6. Change of surface roughness *Ra* of (a) sleeves and (b) shafts

- The change of *Ra* of sleeves lubricated with oil Madit PP 80:
  - the greatest loading – dynamic D1
  - the mean values: D1 = 0.2770, D2 = 0.2329, ST = 0.2100
  - D1 loading had the greatest effect to the observed parameter.
- The change of *Ra* of shafts lubricated with oil Plantohyd 46 S:
  - the greatest loading – dynamic D2
  - the mean values: D1 = 0.0215, D2 = 0.0420, ST = 0.0200
  - D2 loading had the greatest effect to the observed parameter.
- The change of *Ra* of shafts lubricated with oil Madit PP 80:
  - the greatest loading – dynamic D2
  - the mean values: D1 = 0.0440, D2 = 0.0505, ST = 0.0150
  - D2 loading had the greatest effect to the observed parameter.

The results are processed as the mean values of the change of absolute deviation of cylindricity ($\Delta C = \Delta C_2 - \Delta C_1$) of the tested pair (separately for sleeves and for shafts) and are presented in Tables 1 and 2. Based on these results, we may state the following:

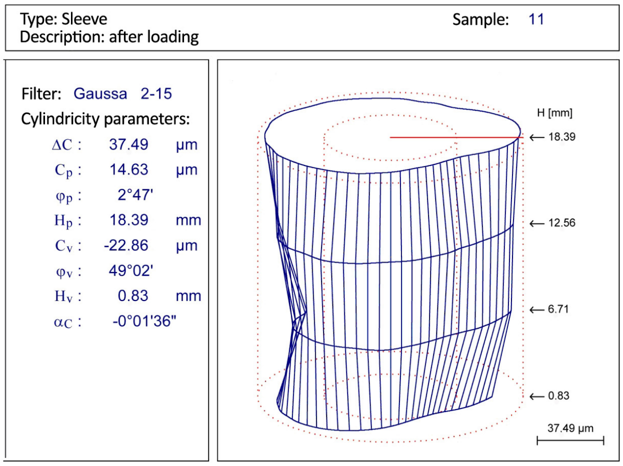

Fig. 7. Results of cylindricity of sleeve after loading regime ST, oil PP80 (sample No. 11)

- the change of cylindricity deviation in sleeves is significantly higher in comparison with shafts,
- the change of cylindricity deviation in sleeves is significantly higher in the environment lubricated with the oil PP 80 compared to the oil Plantohyd 46 S; the maximum value of deviation was 51.494 µm in the loading regime D2,
- the change of cylindricity deviation in shafts loaded dynamically was higher in the environment lubricated with the oil Plantohyd 46 S – the highest value was observed again in the loading regime D1, and that was 3.348 µm,
- the change of cylindricity deviation in dynamic loading is higher in comparison with static loading, while the highest values of change were recorded in sleeves loaded with the regime D2. The cylindricity deviations in shafts loaded with the regimes D1 and D2 do not show significant differences.

Fig. 7 shows selected measurement protocol of cylindricity changes in terms of loading regimes and oil types. Based on these protocols, it is possible to create a realistic idea about how the cylindricity changes of sleeves and shafts were measured and recorded, as well as about the influence of simulated loading regime on the specified parameter.

CONCLUSION

Tribological experiments were performed in order to verify and compare the dynamic and static loading in conditions of the experiment. The experiments explicitly confirmed different effect of

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the new ways of loading on the size of wear and the change of geometry of the selected material pairs. The loading methods based on the randomly generated signal (processed by the statistical dynamics apparatus) had different courses of power spectral density. The mean value of dynamic loading methods was equal to the value of static loading. Dynamically loaded samples showed higher weight losses compared to the static load in conditions of the experiment. This effect was even more significant in environment lubricated with mineral oil. In terms of changes of microgeometry and macrogeometry the experiments clearly proved that dynamic loading methods had a greater effect on these changes than the static ones. Higher values were again obtained in environment lubricated with mineral oil. The statistical analysis of experimental results confirmed the significant effect of dynamic loading methods on mentioned parameters. Agricultural and also other industrial machines are loaded mainly dynamically in operation. The loading method as well as the type of lubricant may significantly affect the durability of friction nodes of these machines. The use of organic oils for lubrication of machinery friction nodes appears to be a suitable alternative not only in terms of environment but also in terms of reducing losses and downtimes.

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