

STUDY OF GREASE BEHAVIOUR IN A STARVED ELASTOHYDRODYNAMICALLY LUBRICATED CONTACT

Petr Svoboda, David Kostal, Jiri Kunak, Ivan Krupka,
Brno University of Technology, Faculty of Mechanical Engineering,
Institute of Machine and Industrial Design,
Technicka 2896/2, 616 69 Brno, Czech Republic

e-mail: svoboda.pe@fme.vutbr.cz

This paper is an experimental study of grease lubrication in a starved elasto-hydrodynamic lubricated (EHL) contact. Lubricating film thickness is measured with tribological experimental device ball-on-disc using optical interferometry and high speed camera. The lubricants used were commercial greases with a various kinematic viscosities, additives and thickeners formulated for low and high-speed applications. The experiment is aimed at a comparison of results acquired by ball-on-disc device and full scale axial bearing. In addition, this paper also investigates the influence of number of the rolling elements (overrolling time) on the resulting film thickness. Experiments confirm the presence of replenishment mechanism caused by relative motion of the surfaces, which generates base oil flow into the inlet of the contact.

Keywords:
grease, starvation, EHD lubrication

1. Introduction

In the rolling bearing there is always a slight slippage between the rolling elements and bearing ring. The rolling element is separated by a lubricant in the bearing ring, which greatly reduces the pressure, friction, wear and bearing life. Lubricants are not limited only to mineral oils; dry lubricant or greases are also used. Specifically greases are used in more than 80 % of all rolling bearing [Lugt 2009].

The main advantage of grease is its ease to use (no need for reservoir of oil or oil bath), good sealing effect, protection against corrosion and low friction. The grease consists of base oil, thickener and additives, and shows a strong non-Newtonian rheology. To determine the film thickness of grease at elasto-hydrodynamic (EHD) contact, the same calculation model as for oil lubricants (often) cannot be used.

Elasto-hydrodynamic lubrication is a type of lubrication, which appears in lubricated non-conformal contacts, where high pressure is generated, which lead to elastic deformation of the lubricated surfaces [Lugt 2011]. This regime prevails in most of rolling bearings. Since 1971 when Wedeven and Cameron [Wedeven 1971] performed the first study of starving EHL contact, intensive research was dedicated to understand the behaviour of the film thickness in EHL contact. It was achieved excellent correlation between experiments and theoretical calculations, which makes it possible to use high precision handbook of rules for predicting the thickness of the lubricant film [Lubrecht 2001].

However, this model [Lubrecht 2001] is restricted to steady state, a smooth surface and a Newtonian fluid. Therefore, the next step is the implementation of these properties. However, one of the most difficult problems is associated with grease lubrication, because it combines starving lubrication and very complex rheology of lubricants.

Lots of articles dealing with the study of greases and influence of operation conditions on film thickness were already published. One of the first articles dealing with grease published [Astrom 1993] where he performed experiments using a ball-on-disc device.

His results show that with increasing number of revolutions the film thickness decreases, up to a critical value, which may damage

the bearing. This degradation of the film thickness occurs much earlier than the end of life of the bearing, which is the main problem of grease lubrication. The degradation rate of the lubricant is significantly influenced by the mechanism of spontaneous recovery of lubricant to the contact called replenishment.

Comparison of the calculated film thickness (without considering replenishment) with the measured decrease in film thickness was published by [Astrom 1993], in which he proved the existence of replenishment. Astrom explained this replenishment as base oil bleeding out from the grease reservoirs, which was pushed by the ball to the contact track.

In subsequent studies it was found that the replenishment significantly affects not only the operating parameters (speed, temperature, load), but also bearing design, such as presence of a cage or spin of the balls bearings.

Cann further experimented with the relationship between the film thicknesses [Cann 2007], the properties of the lubricant and the 4 variable parameters: oil volume, speed, load and viscosity. Measured film thickness as a function of speed for different parameter settings is plotted in Fig. 1. This graph clearly shows the wide range of starvation speeds and for different lubricants parameters.

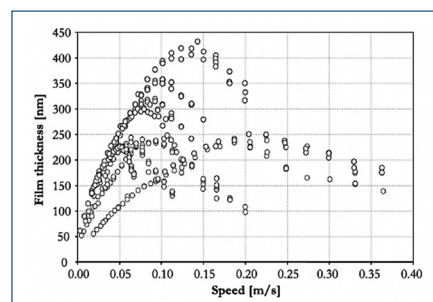


Figure 1. Film thickness as a function of speed [Cann 2007]

The thickness of the lubricant film in contact with non-conformal friction surfaces can be affected by a number of operational factors. The four basic factors that affect lubrication are: the amount of oil, contact surface area, oil viscosity and speed. All these factors may have effect on film thickness. It is obvious that increasing rolling speed increases lubricant film thickness [Svoboda 2013]. The increase in thickness is caused by the movement of friction surfaces during which the lubricant is carried to the contact. The film thickness is mainly affected by speed but also the dynamic viscosity of the lubricant η_0 and pressure-viscosity coefficient α . It is essential to know how bearing works under the starved regime. The fully flooded regime is characterized by a film thickness, which increases with increasing speed, in accordance with the Hamrock–Dowson rules [Hamrock 1977]. However, in the starved regime the film decreases with increasing speed [Svoboda 2013] and it can lead to surface contact and consequently to bearings damage.

Starved lubrication represents one of the transient conditions that bring the risk of the surface damage. Very often the lubricating film is no longer able to ensure full separation of contact surfaces which leads to their contact, wear, noise, vibration and consequent jamming. The film thickness in this regime is often time dependent and its value is governed by lubricant supply. If loss outstrips supply this leads to very thin films, which can no longer fulfill their role of separating the surfaces, and thus component failure can result.

Lugt analysed the influence of temperature influence on the film thickness by conducting long term tests without temperature control [Lugt 2009]. The measured results show that the operating temperature does not remain constant and shows chaotic behaviour. Decreasing film thickness causes increasing temperature which leads to softening of the grease. This softening of the grease results in greater replenishment in to the track contact, thereby recovery of

the film thickness. Subsequently, replenishment of the lubricant in the track from some of this grease will occur, after which full film conditions will once more prevail, followed again by starvation and another film breakdown.

Interesting results in [Cann 2007] were obtained when examining the effect of the ball spin. Fig. 2 clearly shows that the spin motion helps to transfer the lubricant to the track after contact. In the case of no spin, heavily starving mode will soon appear.

The effect of cage design on replenishment was also studied. With grease lubrication, the presence of a cage can have a significant effect upon film thickness. The onset of starvation is delayed until higher speeds with the closely conforming cage. The cage appeared to work by redistributing the grease in the cage/ball contact.

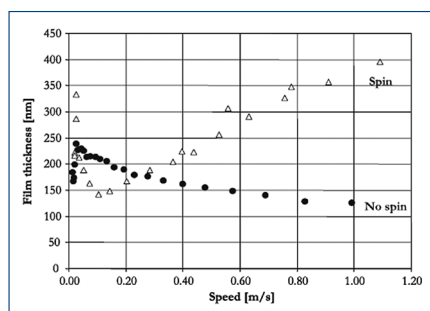


Figure 2. The effect of spin on starvation with grease [Cann 2007]

Furthermore, it was found that not only operating conditions such as rolling speed or temperature has influence on central film thickness, but chemical properties of the grease must be also considered. For example the influence of thickener type [Lugt 2009], thickener content and base oil viscosity [Cann 1999] were thoroughly studied.

In these studies there was number of attempts to create numerical method to predict the film thickness behaviour [Gershuni 2008; Venner 2012], but only a limited success was achieved and use of long-term real conditions tests are still needed.

In most of these articles measurement was made on single contact ball-on-disc bearing simulator. One exception is a study [Baly 2006] where a relationship between full-scale bearing test and laboratory simulation is described on the case of friction. These experiments have shown that friction is reduced for semi-starved contacts but increases dramatically for starved conditions.

However the question remains on whether the results obtained from the laboratory single contact test device transferable to real operating conditions of full scale bearings. The aim of this work is to compare these two approaches (single contact test device together with full scale model) to measuring film thickness. The experimental observation of full-scale model of bearing will help to understand better the behavior of real bearing.

2. Experimental apparatus and conditions

A ball-on-disc laboratory simulation device with single bearing contact (Fig. 3b) was used to establish the behaviour of the film thickness with a range of speed conditions. It consists of steel ball loaded against the glass disc which is driven by electromotor. The top side of the disc is covered with an anti-reflective layer; the lower side

is covered with a layer of chromium. The results have been compared to full scale axial bearing (Fig. 3a); the bearing cage with 16 or 8 balls inside was loaded against the glass disc. To ensure parallelism with disc and steady loading, special stand was constructed [Vrbka 2011]. Schematics of both configurations are shown in Fig. 3.

In a case of full-scale experiments, two series of test were conducted. In the first series axial bearing with a full number of 16th balls was used. Bearing was evenly loaded against the disc by force 5 N per ball via a lever mechanism. Small amount of grease (0.1 g) was applied around the disc. In another series of tests dimensionally identical axial bearing with 8 balls were used. The load was once again adjusted to 5 N per ball. A smaller amount of lubricant was applied on to the disc, considering a smaller number of balls and smaller track which grease must be spread on. The aim was to describe the influence of the number of rolling elements and thus the time elapsed between subsequent overrollings. The measurement conditions were the same as in the case with 16 balls.

In the configuration with full scale bearing, the high speed camera Phantom V710 was used. This camera allows capturing up to 7530 pictures per second at a resolution of 1280 x 1024 pixels. During the experiment, chromatic interferograms are recorded when the individual ball of the axial bearing passes the observed spot. In both configurations the interferograms were evaluated in the Achilles software by using colorimetric interferometry to obtain central film thickness.

Three type of different commercially available grease were used for experiments and are summarized in Tab.1. Before each test the glass disc and the ball were properly cleaned. Small amount of grease (0.5 g for single contact; 0.1 g for full scale) was then applied on the raceway track of the ball. Film thickness measurement for various speed always started with 10 minutes run-in interval in order to obtain equilibrium state.

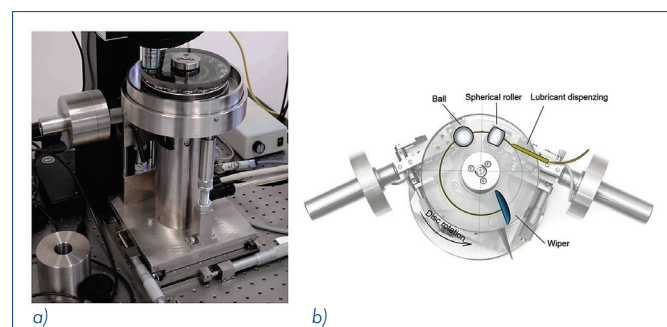


Figure 3. Experimental apparatus a) Full-scale axial bearing[Vrbka 2011]; b) Single contact simulation device [Svoboda 2011]

3. Results and discussion

3.1 Film thickness measurement with single contact simulation device

Most tribological experimental measurements of the film thickness of greases or oils are carried out on laboratory simulators bearing contact ball-on-disc. Therefore in the first series of experiments same approach was used as comparison and measurements were conducted on tribometer with a single contact ball-on-disc configuration.

Label	Commercial designation	Kinematic viscosity at 25°C	Consistency – NLGI	Base oil/additives	Thickener
A	LA 2	130	2	Mineral oil/EP	Lithium soap
B	Ekolube Grease Teflon	200	2	Mineral oil/PTFE	Lithium soap
C	A 00	350	00	Mineral oil/adhesive additives	Al soap

Table 1. Summary of grease properties

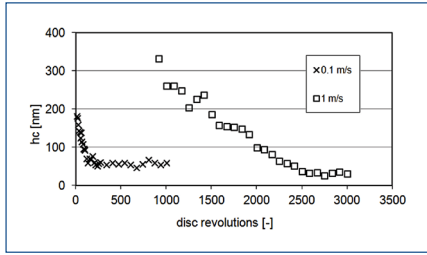


Figure 4. Grease "A" – the influence of disc revolution on film thickness at two different speeds

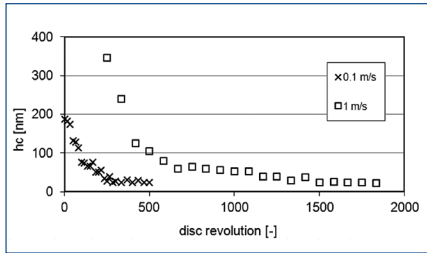


Figure 5. Grease "B" – the influence of disc revolution on film thickness at two different speeds

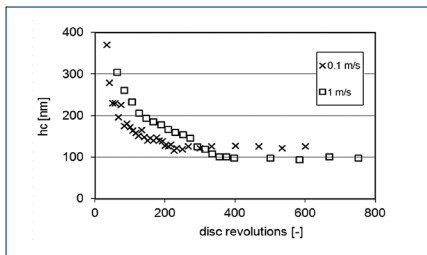


Figure 6. Grease "C" – the influence of disc revolution on film thickness at two different speeds

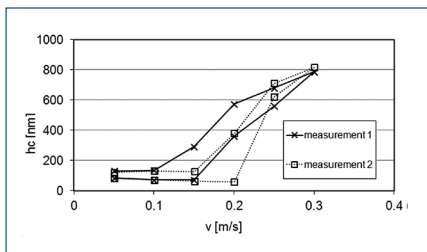


Figure 7. Grease "A" – the influence of speed on film thickness; two consecutive measurements

The steel ball was loaded by force of 10 N against a glass disc via a lever mechanism. A small amount of lubricant (0.5 g) was applied on the disc and great care was taken on its even distribution across the disk. Influence of number of revolutions on the film thickness was measured at constant speed and temperature. First data was captured immediately after reaching the desired speed. Measurements were terminated after reaching steady state, when the film thickness no longer decreases. To ensure measurement repeatability, each experiment was repeated three times.

The plotted values in Fig. 4-6 represent the average value of the three measurements. The degradation rates of the film thickness for each grease at constant speed of 0.1 m/s and 1 m/s are compared.

In all cases the film thickness decreases rapidly at the start of the measurement. This initial rapid decrease is caused by pushing the grease from the track contact. The film thickness was then stabilized to values in the range of 40 to 120 nm, depending on the type of lubricant. At this stage, the lubricating film consists only

of base oil, which bleeding from the reservoir displaced around the track. Effect of gradual degradation of the film thickness and spontaneous recovery of the lubricating film (replenishment) seem to be in equilibrium and therefore the thickness of the film stabilized at constant values.

The graph also shows that the times to reach steady state of resulting film thickness are significantly affected by speed. In the first stage, when a large amount of lubricant is in the contact, fully flooded regime takes place and the film thickness is higher at higher speeds. With the increasing number of revolutions starvation mode prevails, where film thickness decreases to a lower value at higher speed.

The speed also affects the film thickness at steady state as a function of speed. The experiment five minutes run in process took place before the measurements to ensure an even distribution of the grease and to overcome the first phase of rapid film thickness decrease. Once the grease was positioned around the track the rig was run for a 10 minutes to ensure an even distribution of the grease and to overcome the first phase of rapid film thickness decrease. The test was carried out by slowly increasing the speed while measuring the film thickness in the centre of the contact. Therefore, at each step change the speed was held constant until the film thickness had stabilized. Once stabilization had been achieved the speed was increased again. After reaching the maximum speed, the measurement continued in reverse order, when the speed slowly decreased. Typically three readings are taken at each speed level and the average value determined and plotted to Fig. 7.

Two consecutive measurements are shown in this diagram. It can be seen that at low speeds severe starvation occurs and the film thickness levels are below 100 nm. With increasing speed, the film thickness slightly decreases further for both measurements. After reaching the speed of 0.2 m/s, the film thickness starts to increase rapidly. With further increasing of the speed, the film thickness increases accordingly up to very high values above 800 nm. However, when the speed starts to drop again, the film thickness values are higher by 20-50 nm. The shift in the starvation speed on Fig. 7 is caused by different run-in times. While the first measurement started after 5 minutes, the second measurement was conducted after 10 minutes run-in process at constant speed. This is another proof of progressing film thickness degradation over time.

3.2 The film thickness measurement with full-scale simulator

The next series of measurements were carried out on full-scale configuration. In the first series of tests axial bearing with a full number of 16th balls was used. The film thickness as a function of speed was measured. Typically three readings are taken at each speed level.

The influence of the applied grease volume is evident from Fig. 8. When applying 0.2 g or more grease, fully flooded regime took place. Further increase in the volume of applied grease of 2 g has no influence on the resulting film thickness. By applying a smaller amount of lubricant of 0.1 g, starvation regime takes place. In the case of grease "A", this starvation exhibits as overall small, film thickness and as a diversion from the linear characteristics of the fully flooded regime.

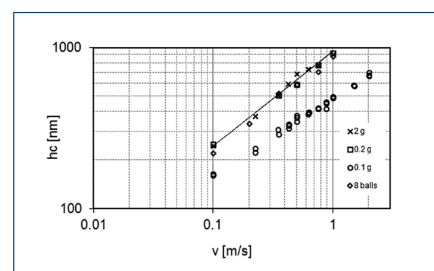


Figure 8. Full-scale configuration; grease "A" – the influence of speed on film thickness

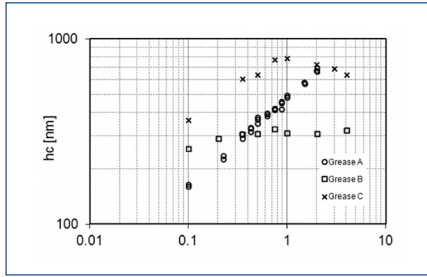


Figure 9. Full-scale configuration; comparison of all lubricants – the influence of speed on film thickness

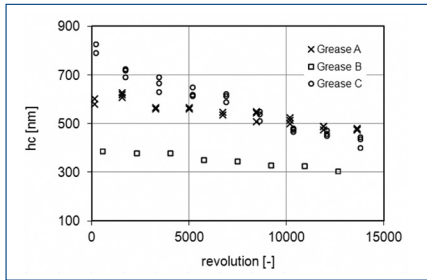


Figure 10. Full-scale configuration; comparison of all lubricants – the influence of disc revolution on film thickness

Comparison of various lubricants and their film thickness is shown in Fig. 9. While grease “A” shows increasing film thickness throughout the entire speed range, grease “C” shows a typical curve with the transition from a fully flooded to starvation regime at the speed of approximately 1 m/s. The film thickness of the grease “B”, which contains solid PTFE additives, increases only slightly. This is probably caused by these solid additives which have a stabilizing effect on the film thickness in the lubricated contact.

The film thickness as function of number of revolutions for all three greases at constant speed 1 m/s are plotted in the Fig. 10. Three readings are taken every 10 minutes and the average values are showed. All three greases show a gradual degradation of the film thickness during the whole measurement. The rate of this degradation is different for different lubricants. When applying the

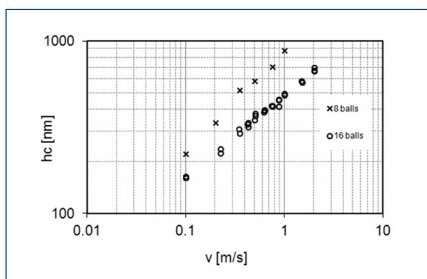


Figure 11. Full-scale configuration; grease “A” – the influence of number of balls on film thickness

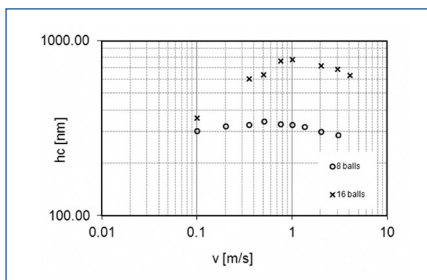


Figure 12. Full-scale configuration; grease “B” – the influence of number of balls on film thickness

same amount of lubricant, grease “C” initially shows the highest film thickness, but the degradation is very fast. Grease “B” shows the smallest change of film thickness during the whole measurement. Generally highest film thickness and the relatively slow degradation were observed in measurement with grease “A”.

On Fig. 11–13 there is the comparison of measured film thickness with 8 and 16 balls for each of the greases as a function of speed. The influence of the number of rolling elements is different for each of the grease. In the case of 8 balls, grease “A” generally shows higher film thickness. Same values were added to the diagram in Fig. 8, where it is clear to show that a fully flooded regime prevailed. In the case of 8 balls, grease “C” shows smaller film thickness (Fig. 13). This suggests that in this case, capillary forces of the balls have prevailing influence on the film thickness replenishment. Higher overrolling frequency helps to replenish the film thickness in the contact. To some extent, this effect is also observed in the case of grease “B”. The film thickness behaviour shows a typical starvation curve (Fig. 12). It is obvious that in this case the speed of 0.5 m/s the film thickness starts to decrease slowly.

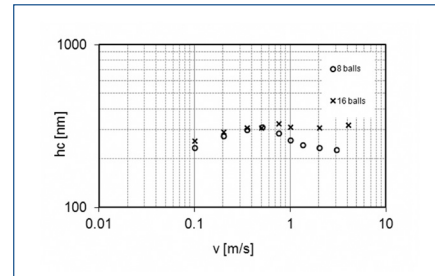


Figure 13. Full-scale configuration; grease “C” – the influence of number of balls on film thickness

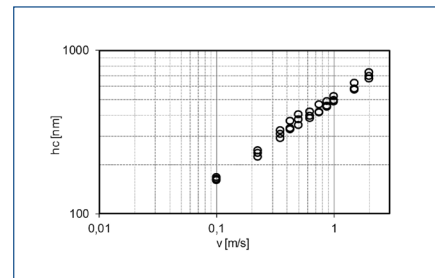


Figure 14. Full-scale; 16 balls, grease A – influence of speed on central film thickness; three measurement under same operation condition

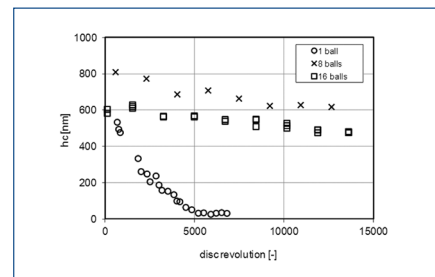


Figure 15. Grease A; influence of number of revolution on central film thickness – comparison of the results measured on ball-on-disc and full-scale device

Repeatability of experiments is shown in Fig. 14, where central film thickness with increasing speed on a single contact device was measured. In all the experiments with grease, there is much greater spread of measured values than in the case of oils. This is due to the strong dependence of replenishment on the creation of grease reservoir on the edge of the contact track or on the bearing cage. Dynamic effects influence the placement of these reservoirs, and thus the replenishment and the resulting film thickness of lubricant in contact.

Thus range of values is higher at higher speeds. Nevertheless film thickness dispersion was mostly under 10 %.

In Fig.15 is shown a comparison of the two measurement approaches (ball-on-disc and full-scale). It is clear that the measured results differ significantly. This difference is caused not only by the number of rolling elements, but also by the presence of the bearing cage. For instance cage instability can provide an additional redistribution mechanism.

4. Conclusions

In this article, the grease behaviour in a starved elastohydrodynamically lubricated contact is reported. Some important experimental results and inferences are as follows:

The results of the experiments with the single contact ball-on-disc device confirms the presence of replenishment mechanism caused by relative motion of the surfaces, which generates base oil flow into the inlet of the contact reported in [Cann 1996].

While the film thickness of the grease "A" was higher in the case of fewer balls, the film thickness of the grease "B" and "C" was lower. It is clear that the number of balls had different effect on all types of lubricants. In case of grease "B" and "C" the influence of capillary forces prevailed thus the increasing overrolling frequency helped replenish the lubrication film. This did not occur in grease "A" lubricated contacts where probably due to its lower viscosity the capillary forces are not strong enough to sufficiently replenish the lubrication film.

Measurements on the single contact ball-on-disc device showed that film thickness decrease rapidly at low range of revolution. The film thickness is than stabilized at very low values. On the contrary, if the full scale bearing with cage is used, the film thickness drops much more slowly and the overall film thickness was higher. Obviously the presence of the bearing cage had significant influence on the film thickness behaviour in the rolling contact.

It has been found that both approaches (full-scale and single contact ball-on-disc) are not comparable. While measurement on the full-scale test device provides overall information on bearing behaviour under practical operation conditions. On the other hand, with the single contact ball-on-disc device it is possible to directly observe all the mechanisms and processes involved in grease lubrication, and study them individually. Therefore, it is clear that neither of these approaches can substitute for the other. These two experimental methods are complementary, not alternatives.

Acknowledgments

This work is an output of cooperation between Czech Science Foundation under project no.: 13-30879P and NETME Centre, regional R&D centre built with the financial support from the Operational Programme Research and Development for Innovations within the project NETME Centre (New Technologies for Mechanical Engineering), Reg. No. CZ.1.05/2.1.00/01.0002 and, in the follow-up sustainability stage, supported through NETME CENTRE PLUS (LO1202) by financial means from the Ministry of Education, Youth and Sports under the „National Sustainability Programme I“. David Kostal would like to thank JCOMM that he can be the Brno Ph.D. Talent scholarship holder (Funded by Brno City Municipality).

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Contacts

Ing. Petr Svoboda, Ph.D., Brno University of Technology
Faculty of Mechanical Engineering
Institute of Machine and Industrial Design
Technicka 2896/2, 616 69 Brno, Czech Republic
tel.: +420 541 143 215, e-mail: svoboda.pe@fme.vutbr.cz
<http://uk.fme.vutbr.cz/>

Ing. David Kostal, Brno University of Technology,
Faculty of Mechanical Engineering
Institute of Machine and Industrial Design
Technicka 2896/2, 616 69 Brno, Czech Republic
tel.: +420 541 143 227, e-mail: kostal@fme.vutbr.cz

Bc. Jiri Kunak, Brno University of Technology,
Faculty of Mechanical Engineering
Technicka 2896/2, 616 69 Brno, Czech Republic
e-mail: y115773@stud.fme.vutbr.cz

prof. Ing. Ivan Krupka, Ph.D., Brno University of Technology,
Faculty of Mechanical Engineering
Institute of Machine and Industrial Design
Technicka 2896/2, 616 69 Brno, Czech Republic
tel.: +420 541 142 723, e-mail: krupka@fme.vutbr.cz