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RESTORING THE PASSIVITY OF SHUNT DAMPING CIRCUITS BASED ON THE SYNTHETIC INDUCTANCE BY THERMAL ENERGY HARVESTING

ABSTRACT

For decades people have used ambient energy, e.g., that of rushing streams or wind to obtain usable power. Starting with very low energy conversion, through constant development we have now reached the stage of extensive possibilities of harvesting the energy from the environment we live in. Today, there exist almost unconstrained opportunities to energize a broad spectrum of devices by energy available almost anywhere and of whichever form. One of the great advantages of energy harvesting is to make small electronic devices autonomous eliminating the need of power supply and maintenance. Shunt damping systems are unfavorably influenced by the size and mass of the coil inductors. While substituting bulky inductors with synthetic inductors one losses the passivity of the system gaining its practicability. Nevertheless, in order to outperform the actively driven systems, it is indispensable to return the passive properties of the system maintaining its performance. This paper presents the feasibility study of powering the passive shunt damping devices by the work that is lost irrevocably in a bearing node. The heat generated in a bearing is converted via the thermoelectric phenomenon and then used to power the synthetic inductance circuitry. In the paper it is shown that the required power levels can be satisfied by the thermoelectric generator paired to a moderately loaded bearing.

PRZYWRÓCENIE PASYWNEGO CHARAKTERU METODZIE TŁUMIENIA DRGAŃ OPARTEJ O MATERIAŁY PIEZOELEKTRYCZNE PRZEZ WYKORZYSTANIE TECHNIKI POZYSKIWANIA ENERGII STRAT CIEPLNYCH

Od zawsze ludzie wykorzystywali energię dostępną w ich otoczeniu i przekształcali ją w użyteczną pracę mechaniczną. Stopniowo priorytetowym zadaniem stało się pozyskiwanie energii w formie energii elektrycznej. Z początku niewielka sprawność i koszt inwestycyjny nie pozwalał na szerokie wykorzystanie technik pozyskiwania energii, dzisiaj stajemy przed niespotykanym wcześniej zapotrzebowaniem na energię, a przede wszystkim mamy możliwość generowania energii ze źródeł różnego typu i wielkości dostępnych w naszym otoczeniu. Technika pozyskiwania (zbierania) energii oferuje szeroki potencjał możliwości zasilania urządzeń elektronicznych małych mocy, przekształcając je w jednostki autonomiczne niewymagające zasilania ani okresowej wymiany magazynu energii. Technika tłumienia drgań z wykorzystaniem materiałów piezoelektrycznych ograniczona jest przez wymaganą synchronizację drgań konstrukcji i obwodu rezonansowego, która niesie za sobą konieczność użycia cewek indukcyjnych o znacznych wymiarach gabarytowych i masie. Istnieje możliwość zastąpienia tych elementów przez sztuczną indukcyjność realizowaną jako układ elektroniczny za pomocą wzmacniaczy operacyjnych kosztem utraty pasywnego charakteru metody. W artykule zaprezentowano studium wykonalności układu tłumienia drgań wykorzystującego sztuczną indukcyjność, ale zasilaną ze źródła energii pozyskiwanej ze strat cieplnych łożyska. Artykuł udowadnia, że dla szerokiego spektrum przypadków połączenie techniki pozyskiwania energii oraz techniki wykorzystujących bierne obwody (shunt damping) jest korzystne.

1. INTRODUCTION

The shaft support, besides its obvious function, serves as a transfer path between the shaft mounted elements (e.g. meshing gears) and machine housing or foundation. The mechanical interactions give rise to structure-borne noise or cause vibrations to appear. The classical means of reducing the above mentioned phenomena involve the stiffening of the construction or adding mass, which often is prohibitively expensive and unacceptable. Other solutions, to name a few, are sound absorbing materials, source encapsulation, viscoelastic materials in constrained or free layer damping arrangements and bunch of active methods including AVC [1] and ASAC [2] techniques.

Passivity is an important asset, thus even if not guaranteeing the highest performance the passive methods are those that have gained the most interest in real life applications. There has not been any attempts to combine the semi-passive piezoelectric shunted circuits (i.e. ones with synthetic inductance) with thermal harvesting sources present in rotating machines as internal bearing losses. An argument for such a combination would be that having addressed the vibrations in close proximity to the bearing less vibration transfer paths have to be controlled (Stallaert, Devos, Pinte,

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[1] Acitve Vibration Control
[2] Active Structural Acoustic Control

Symens 2008). Furthermore, each bearing irrespective of its type, load and lubricant used generates some amount of heat due to the rolling frictional moment, sliding frictional moment, oil drag and other factors contributing to the overall frictional moment of the bearing. Moreover, rotating machinery is characterized by the periodic disturbance with a fundamental frequency proportional to the machine rotational speed, which is favorable for shunted piezoelectrics as they have to be tuned to the frequency of operation. In the case frequencies that are not known in advance adaptive shunts are applicable.

The paper presents the feasibility study of the autonomous piezoelectric damper located near a bearing node of a rotating machinery that is powered via thermoelectric generator eliminating the need for an external power supply. The first section of the paper describes the idea of the damper in relation to the existing solutions. Afterwards the analysis tools will be presented together with experimentally obtained results. In the next two paragraphs the results of the analysis will be discussed and the conclusions based on the conducted research will be drawn.

2. STATE OF THE ART IN THE FIELD OF VIBRATIONS TREATMENT AND THERMAL ENERGY SCAVENGING

The most often exploited technique of vibration damping is via viscoelastic materials, thanks to their high loss factor (Nashif et al. 1985). To overcome the shortcomings of the passive viscoelastic materials used as vibration dampers the research community has recently gained interest in smart materials. An example of the aforementioned are shape memory alloys used in APT[3] and ASET[4] technique. Also, it has been noticed that piezoelectric materials show both high stiffness as well they can exhibit high loss factor values. Many studies (Kneba and Makowski 2004, Cudney et al. 1994, Ringwelski et al. 2011, Ushijima 1993) reveal its high potential when actively driven, nevertheless the damping effect is still significant for the passively operated piezoelectrics (Caruso 2001). Shunted piezoelectric (passive) technique has been presented in the work of (Hagood and Von Flotow 1991). The resonant (R-L) circuits are the first that have been proposed and are most referenced by the research community. With the work of Hollkamp (Hollkamp 1994) the multi-modal damping has been introduced in the form of parallel R-L-C branches. The next advancements in this technique was brought by Wu (Wu 1998) with a current blocking circuit composed of parallel branches containing resonant R-L and filtering R-C components. All of the above circuits are called linear shunts. Within the passive shunts one can distinguish a group of shunts that is based on the switching circuitry and in opposition to previously mentioned they are called non-linear shunts. In general, shunting circuits may be divided into several categories, i. e., active and passive shunts, adaptive and non-adaptive shunts or single and distributed shunts.

The important shortcoming of passive piezoelectric dampers is the fact that for high efficiency (resonant shunting) large both in size and value inductors are necessary making the multi-modal shunts not feasible for practical implementations. The problem has been partially solved by introducing the synthetic inductors by Riordan (1967) and Antoniou (1969). A large inductance could be substituted by lightweight electronic circuit, which requires a power supply, though. The solution has to be a tradeoff between the locally operated low efficiency damper and effective damper that requires a power supply. There have been made several attempts aiming to introduce self-powered devices. The Strain Amplitude Minimization Patch (STAMP) damper was presented in (Konak et al. 1997, 2001) as a self-powered shunt vibration controller. However, the achieved performance was proved to be worse than this of externally powered switched inductor designs. Similar tryouts were presented in (Niederberger 2005). The device was composed of two piezoelectrics, one of which was performing a role of energy harvester powering the MOSFET gate drives and timing circuitry. Stand-alone self-powered devices has been proposed for energy harvesting, nevertheless pre biasing of the piezoelectric apart from increasing the power output requires a fraction of produced energy to operate (Dicken et al. 2009). The piezoelectric energy harvesting devices are typically characterized by light coupling and are not suitable to create a synergic combination with vibration dampers.

Assuming the vibrations are damped out via a shunted piezoelectric patch, in some cases the synthetic inductor is the only element of such a system that requires external power to operate. For others, there will be additional energy sinks in the form of switching circuitry. The synthetic inductor is a circuit that has nearly constant power consumption and it has to be powered continuously to serve its function. Several types of synthetic inductors have been developed so far. First constructions were based on operational amplifiers and underwent substantial change in performance throughout the years, mainly due to advancement in electronics and scale of integration. The classic constructions (Horowitz and Hill 1989) allow for a large Q factor values while being relatively simple circuits. Based on the operational amplifiers some authors proposed a self adaptive inductor design (Greaves et al. 2008) to be used in shunted piezoelectric applications. The important discovery was that despite the change in inductance the values of the power consumption remained practically unchanged at the level of 100 mW. It is worth to note that here the consumption has been proved experimentally with no prior power optimization. Therefore, the presumed power demand of the device delivered

[3] Active Property Tuning
[4] Active Strain Energy Tuning

to the end-user is lower. The studied inductance values differed from a fraction of henry to a couple of henries which is a typical range for shunted piezoelectric actuators working in the frequency range of a few to several hundred hertz. The high Q factors resulted from low internal resistance of the synthetic inductor compared to its wounded counterpart. A similar structure of the synthetic inductors has been tested showing power consumption at the level of 150-400 mW depending on DC bus voltage (Luo et al. 2007). The same authors proposed the synthetic inductor construction based on the power electronics instead of operational amplifiers. The result was a decrease in the power consumption by an order of magnitude. Experimental tests showed the power consumption at the level of 11 mW for the value of 1 H, 100 kHz switching frequency and 5 V DC bus.

(Ortiz et al. 2007). The possible power management strategies and adaptive duty cycling for the wireless sensor nodes have been introduced in (Kansal et al. 2006). Despite the fact that the first research on thermoelectricity and bearing cooling is dated back to 1963 (Mims 1961), and continued in (Tadashi and Fumito 1983), the idea of an energy harvesting system using the heat waste of a rotating bearing was not introduced until (Minoru 2004) and in the form of a housing integrated device in (Kenji 2008). There are no research papers on successful implementation of thermoelectric harvesters in the machine bearing node, however, the research topic has been noticed and is being explored (Micropelt 2011, Nextreme Thermal Solutions 2011, Sentient Corporation 2011). The evolution of shunt damping systems is shown in figure 1.

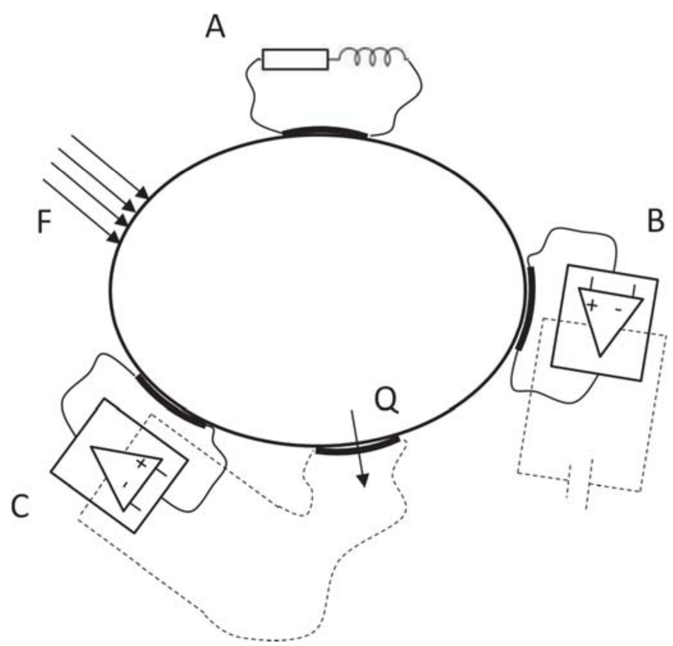

Fig. 1. The schematic representation of the shunt damping system evolution. A – passive, linear system; B – semi-passive system; C – proposed solution with restored passivity

Thermoelectricity enables a solid state conversion between heat flux passing through the structure of the generator into usable electric power. Thermoelectric modules can operate reliably even in a harsh environment as long as persistent thermal gradients exist. However, low conversion efficiency is still an obstacle in many potential applications (Fleurial et al. 1999). Many researches have been conducted on the topic of low-temperature energy harvesting e.g. involving human body heat, starting with (Starner 1996), through ones on Body Area Network applications (Starner 1996, Leonov et al. 2007), to those on implantable bio-sensors (Mitcheson 2010). A wireless network based on a thermoelectric generators was presented in (Mateu et al. 2006). The theoretical considerations of such a network, from the point of view of a single node, are presented and analyzed in

3. IDEA OF AUTONOMOUS VIBRATION DAMPER

The concept of a bearing node that is able to supply energy to the semi passively operated piezoelectric is discussed in consecutive chapters. The idea of an autonomous vibration damper refers to all passive and active shunt circuit topologies but linear resistive and linear capacitive (Fig. 2) – both of each are characterized by poor damping capabilities, though.

To overcome the typical flaw of the shunt damping approach, i.e., bulky inductor having high internal resistance value, the wounded inductor can be exchanged with an electronic circuit having the required electrical characteristic.

As a result, the power supply has to be delivered to the circuit. This is the case for active and non-linear shunts as well.

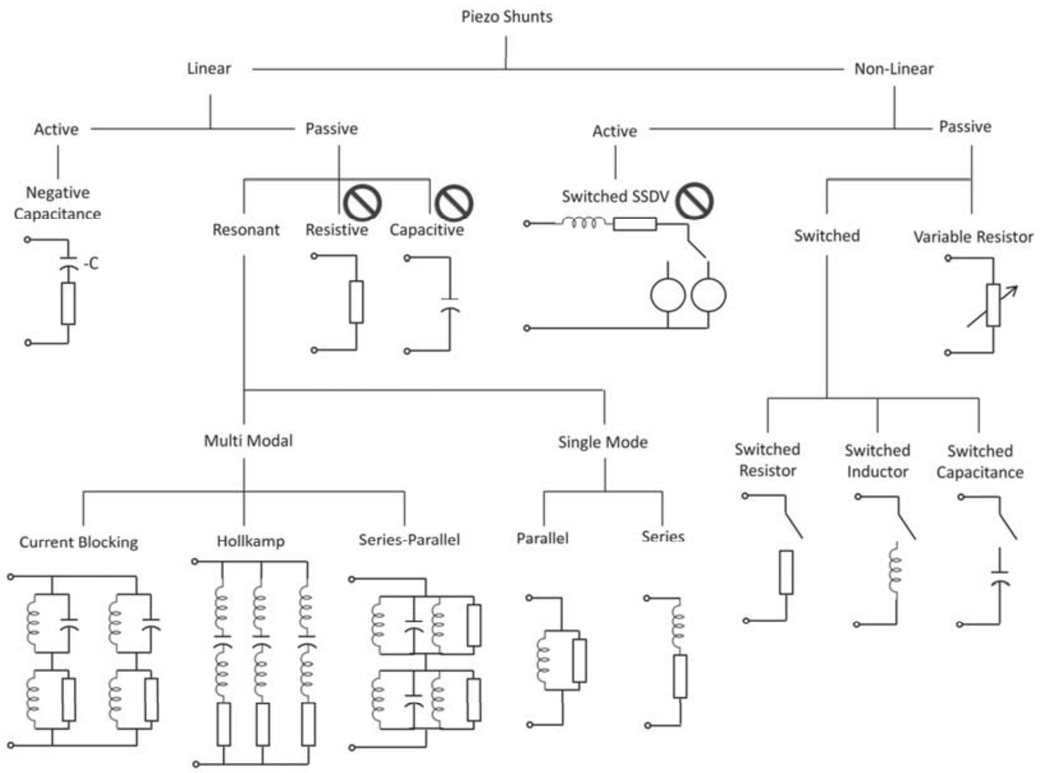

Fig. 2. Classification of shunt damping systems; Prohibition sign shows the shunting circuits that do not profit from the proposed idea, remaining topologies are potential application field of the energy harvesting based power supply

The source of the electric power may be the thermoelectric harvester on condition the energy production rates match the actual demand of the electronic circuit. This unique approach to the vibration damping via the shunted piezoelectrics was first introduced in (Lubieniecki and Uhl 2012). Irrespective of the harvesting circuit operation being continuous or periodic (working when acceleration level is over a set threshold) the energy neutral operation is guaranteed by maintaining the energy conservation law (Kansal et al. 2007), that states:

$$E_0 + \eta\int_0^T \left[P_s(t) - P_c(t)\right]^+ dt - \int_0^T \left[P_c(t) - P_s(t)\right]^+ dt -$$
$$- \int_0^T P_{leak}(t)\, dt \geq 0 \; \forall T \in [0, \infty) \quad (1)$$

where $[]^+$ operation stands for: $[x]^+ = \begin{Bmatrix} x & x \geq 0 \\ 0 & x < 0 \end{Bmatrix}$,

the P_S and P_C are harvested and consumed power, respectively. E_0, P_{leak} and η stand for energy initially stored in the energy buffer, buffer leakage and combined efficiency of the charge-discharge buffer cycle.

The question raised is if the thermal gradient between the generator junctions for a given rotational speed and loading would be enough to assure the neutral operation of the proposed damper?

A more detailed analysis of the available power levels based on the assumption of energy neutrality together with sensitivity analysis of the construction variables can be found in (Lubieniecki and Uhl 2012).

The important issues of such a system involve the device operation before the full warm-up of the machine (due to thermal capacitances) and transition through resonance at the machine run-up. The proper energy buffer has to be used to enable the device operation in these transient states. In order to verify the correctness of the presented concept the power level of the thermoelectric generator coupled to the medium sized self-aligning ball bearing was experimentally measured for a set of different rotational speeds and constant radial loads. Here, the obtained power levels were compared to the power demand of the synthetic inductors known from the literature.

4. FEASIBILITY STUDY OF THE PROPOSED CONCEPT OF AUTONOMOUS DAMPER

Theoretical model

The general scheme of the bearing node with the harvester is shown in figure 3. The resistive network was chosen so as to introduce the maximum generality of the model. The different scenarios can be built by eliminating elements, by short-circuiting them or giving them infinite-impedance properties. For the sake of simplicity and interest in steady operational condition the thermal mass (capacitance) has been omitted.

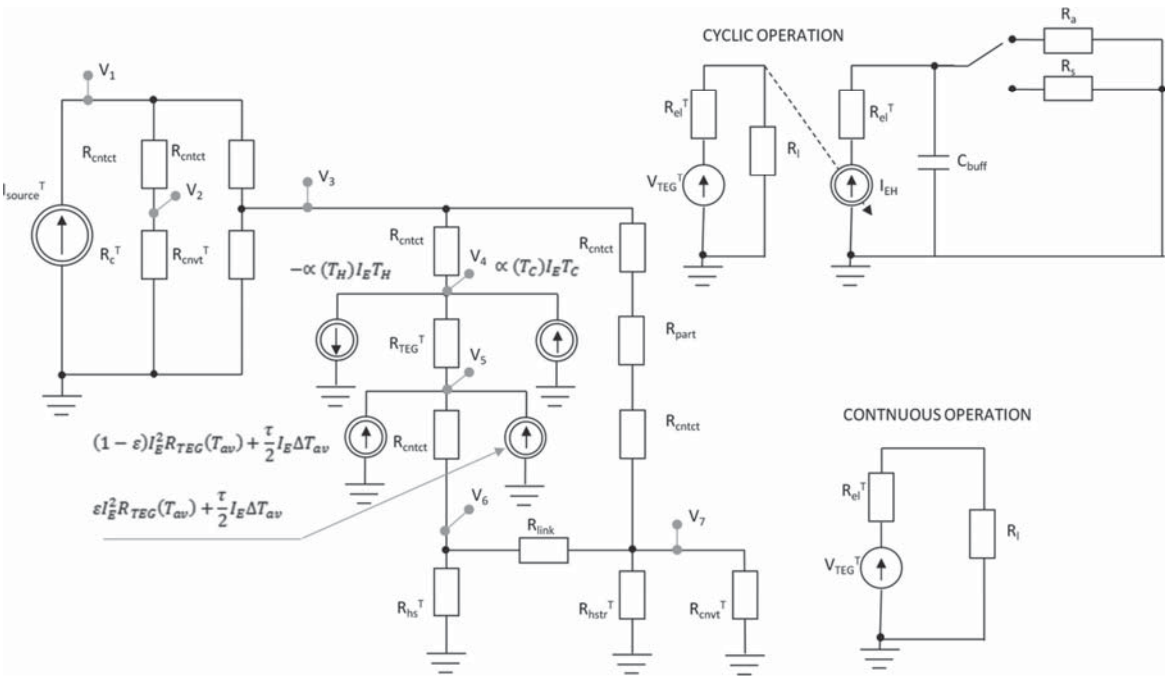

Fig. 3. Equivalent bearing node representation in the form of resistive network with controlled current source components; model includes thermoelectric modules; For the symbol explanations please, refer to (Lubieniecki and Uhl 2012)

Within the proposed model equivalent circuit one can distinguish at least two most characteristic circuit instances:

a) the bearing housing is thermally linked to the machine base but insulated from the bearing, additional heat sinks are required,
b) the bearing housing is thermally insulated from the machine base and the heat source (i.e. bearing) and acts as a heat sink.

The key differentiator between these two variants is the R_{link} (thermal bridge) being a switch-like circuit element. The low resistance of which will lead to the (b) design. It is alledged that simultaneously the R_{part} (insulating partition resistance) element is kept at its high value. Otherwise the thermal current in the branch V_3–V_7 won't allow the high temperature difference between the generator's junctions. The equivalent system model has been built in the form of a resistive network where the thermal resistances are voltage dependent components (the physical meaning of which is temperature dependent). Therefore, the popular circuit solvers may not be favorable environment to solve such a model as it would require not straightforward implementation of dependent resistive elements that cannot be modeled by simple voltage controlled resistors. Such an element allows usually only simple proportional relation while the component constitutive equations to be implemented show strong non-linear behavior. Therefore, the model equations have been directly implemented in the Matlab package. The equations for node voltages of equivalent electrical circuit were obtained by modified nodal analysis (Ruehli and Brennan 1975). Together with constraint equations for the current and voltages sources they create a set of complete equations 2–10 describing the thermal network.

$$T_1 = P_{loss}\left(n_{RPM}, F_r, F_a, T_1, B_{type}, d_o\right) - \frac{(T_1 - T_2)}{R^1_{CNT}} - \frac{(T_1 - T_3)}{R^2_{CNT}} \quad (2)$$

$$T_2 = \frac{(T_2 - T_0)}{R_c(T_2, n_{RPM}, d_0, L_{shaft})} + \frac{(T_2 - T_1)}{R^1_{CNT}} \quad (3)$$

$$T_3 = \frac{(T_3 - T_1)}{R^2_{CNT}} + \frac{(T_3 - T_0)}{R_{CNV}(T_3)} + \frac{(T_3 - T_4)}{R^3_{CNT}} - \frac{(T_3 - T_7)}{R_{part}} \quad (4)$$

$$T_4 = \frac{(T_4 - T_3)}{R^3_{CNT}} + \frac{(T_4 - T_5)}{R^{TH}_{TEG}(T_4, T_5, N_{pair}, A_{pellet} / L_{pellet})} + \\ + N^4_{TEG} \quad (5)$$

$$T_5 = \frac{(T_5 - T_4)}{R^{TH}_{TEG}(T_4, T_5, N_{pair}, A_{pellet} / L_{pellet})} + \frac{(T_5 - T_6)}{R^4_{CNT}} + \\ + N^5_{TEG} \quad (6)$$

$$T_6 = \frac{(T_6 - T_0)}{R_{HS}(T_6, T_0, N_{fins})} + \frac{(T_6 - T_7)}{R_{LINK}} + \frac{(T_6 - T_5)}{R^4_{CNT}} \quad (7)$$

$$T_7 = \frac{(T_7 - T_3)}{R_{PART}} + \frac{(T_7 - T_0)}{R_{HSTR}} + \frac{(T_7 - T_0)}{R_{CNV}(T_7)} + \frac{(T_7 - T_6)}{R_{LINK}} \quad (8)$$

$$N^4_{TEG} = -\alpha\left(T_4, N_{pair}, A_{pellet} / L_{pellet}\right) I T_4 + \\ + \left(1 - J_J\right) I^2 R^{EL}_{TEG}\left(T_{mean}, N_{pair}, A_{pellet} / L_{pellet}\right) + \\ + \frac{\partial \alpha\left(T_4\right)}{2 \partial T} I (T_4 - T_5) \quad (9)$$

$$N_{TEG}^{5} = \alpha\left(T_5, N_{pair}, \frac{A_{pellet}}{L_{pellet}}\right) IT_5 +$$

$$+ J_J I^2 R_{TEG}^{EL}\left(T_{mean}, N_{pair}, \frac{A_{pellet}}{L_{pellet}}\right) + \frac{\partial\alpha(T_5)}{2\partial T} I(T_4 - T_5) \quad (10)$$

The thermal model most far-reaching assumption is that the interfaces of all elements are isothermal surfaces. In general this may be considered to be true for elements of small dimensions and when the heat flow is perpendicular to the faces (no thermal gradients along the surface edges). Having in mind that heat exchange from the machine to the ambient surrounding occurs mainly due to convection process that is a far less efficient heat transport phenomenon than heat conduction in solids it may be stated that the convection is the element shaping the thermal interface and for reasonably small surfaces these interfaces remain isothermal. The aim of the equivalent circuit model is to investigate the harvester power capabilities with the changes of the bearing node structure and hence the changes of its thermal properties. There are several distinct elements of the proposed model that account for different physical phenomena. These are: thermoelectric conversion, natural convection (heat sink, flat surfaces) R_{CNVT}, convective boundary condition on the rotating shaft R_C, internal bearing power loss I_{SOURCE} and contact resistances R_{CNTCT}. The adopted model of thermoelectric generator (Freunek et al. 2009) is based on the thermal network including all thermoelectric effects: Seebeck (α), Peltier (αT) and Thomson (τ) as well as it includes the overall effect of the thermal resistances in the generator structure. It does not account for the module geometry nor for uneven temperature distribution on heat spreaders or internal thermal bridges, though. Heat sink model (R_{HS}) as well as the convection boundary conditions were considered through the dimensional analysis and models given in (Kreith 2000). As the air properties change significantly with temperature, proper look up tables were used in model calculations. The convective heat transfer from a horizontal rotating cylinder was described by (Özerdem 2000). The calculations of bearing thermal loss is based on the SKF model (SKF 2005) and was used together with Walther viscosity model of grease lubricant.

The study starts with elaborating the equivalent model of the thermoelectric energy harvester accounting for specific operational condition in a bearing node. The characteristic thing about the model is that it represents the harvester integrated in the machine and allows investigating the reciprocal relation between the energy yield and the construction the harvester is attached to. The proposed model underwent sensitivity analysis to show which factors are most prone to the affect the harvested power levels. The structural elements of the design have been rated. It was shown that the power yield of the harvester strongly depends on the bearing type it operates on as the power characteristics of the bearings differ significantly (Lubieniecki 2012).

5. EXPERIMENTAL VALIDATION

The possibility of energy harvesting based on the power thermal loss in a bearing has been verified by comparing the experimentally obtained power gain of the harvester with the power consumption reported for synthetic inductors in the literature. The experiment has been conducted in a twofold manner: with bearing housing on a test rig and with the controlled heater in place of the bearing. The experimental setup is organized as follows (Fig. 4): the electric spindle 4 drives a two point supported shaft, the third bearing 2 on the shaft can be shifted giving only the radial load to bearings 1, 3, which were medium sized typical steel self-aligning ball bearings (mean diameter equals 46 mm). The tem-

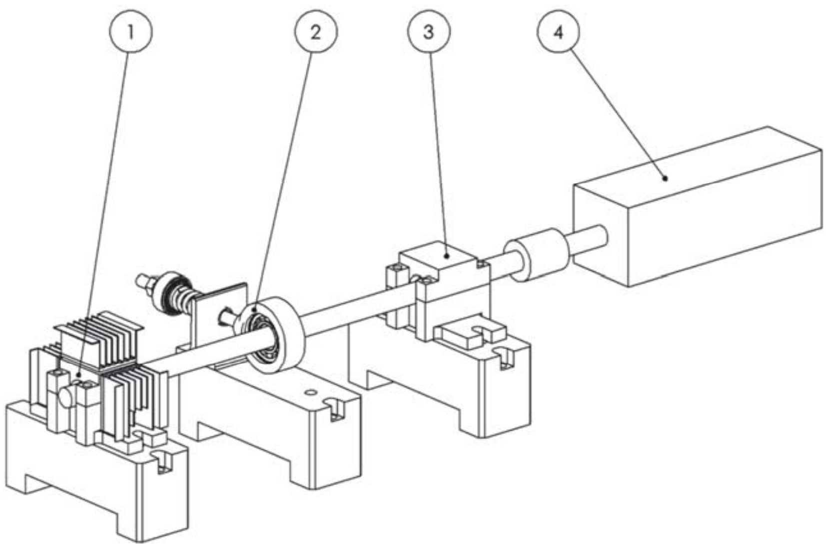

Fig. 4. The experimental setup: 1 – the bearing housing equipped with thermoelectric modules, 2 – radial load excitation, 3 – bearing housing, 4 – electric spindle

peratures of the thermoelectric generator's (TEG) junctions together with the open circuit voltage has been measured under a load in the range 150–900 N while the speed has been changed in a range of 500–3000 rpm (Fig. 5). After any change in the operational condition the measurements have been taken after the system reaches the steady state. In the case of the controlled resistive heater replacing the bearing the harvested power level was measured for both the matched resistive load conditions and as the power output of the harvesting circuitry.

The power that could be harvested with respect to the theoretical power loss in a bearing is presented on Figure 6. The theoretical power available is marked with the dashed line – the circles and crosses show experimental measurements and numerical predictions, respectively. As the voltage output of the generator ranges from 20 mV up to 750 mV the two conversion strategies have been investigated. Two different voltage converters and power management architecture have been compared: Ultralow Voltage Step-Up Converter and Power Manager (LTC3108) and 400 mA Step-Up DC/DC Converter with Maximum Power Point Control and 250 mV Start-Up (LTC3105). The first pf the mentioned devices enables energy conversion and storage starting with as low voltages as 20 mV, however, its conversion efficiency does not exceed 35%. The latter operates when the input voltage exceeds 250 mV and offers the conversion efficiency in the range of 40–90% for the inputs equal 0.25 and 2.5 V, respectively. It is noteworthy that for LTC3108 the conversion efficiency drops as the bearing loss rises.

6. DISCUSSION OF RESULTS

Having kept the operation of the harvester as neutral the power levels have been analyzed for both the continuous and periodic operation of the load. The assumed continuous power consumption of the single synthetic inductance is at the level of 10 mW. The power levels appropriate for operating the synthetic inductor circuitry are feasible over some bearing loss level or with the use of larger number of generators. The LTC3108 can never supply the required amount of energy when coupled with only one thermoelectric generator operating at low temperature difference (Fig. 6). On the other hand, the sufficient amount of energy is delivered by LTC3105 when the bearing power loss equals around 14 W which corresponded to the temperature difference of 4.18 K on the TEG's junctions in the analyzed case. The maximum temperature difference obtained in the experiments was at the level of 16 K (around 30 K between the bearing and the surrounding). One can easily point the applications for which both the absolute temperatures and temperature difference are much higher (e. g. in case of introducing the thermal insulating partitions). Nevertheless, every single aplication has to be followed by a careful feasibility study due to bearing node construction details, presence of other heat sources, conductivity of the materials, heat bypasses etc.

The power level (Fig. 6) available in periodic operation mode stays at the proper level for a typical sensor and wireless transmission even for low power losses in a bearing. The measurements can be taken every 30 seconds in the worst case scenario (for the lowest measured power gain).

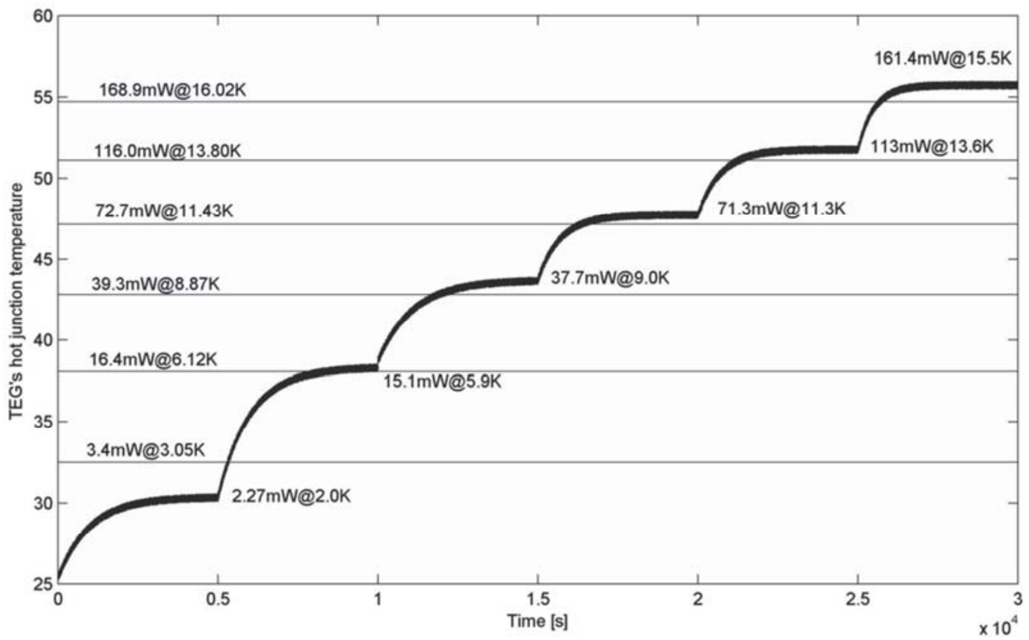

Fig. 5. The expemplary measured time series of the temperature of TEG's hot junction; Horizontal lines show the numerical predictions of this temperature in the steady state. The labels show the theoretical (matched impedance) and measured power levels and corresponding temperature difference on the TEG's junctions; The experiment involved constant radial load of 957 N and speed change in the range from 500–3000 rpm

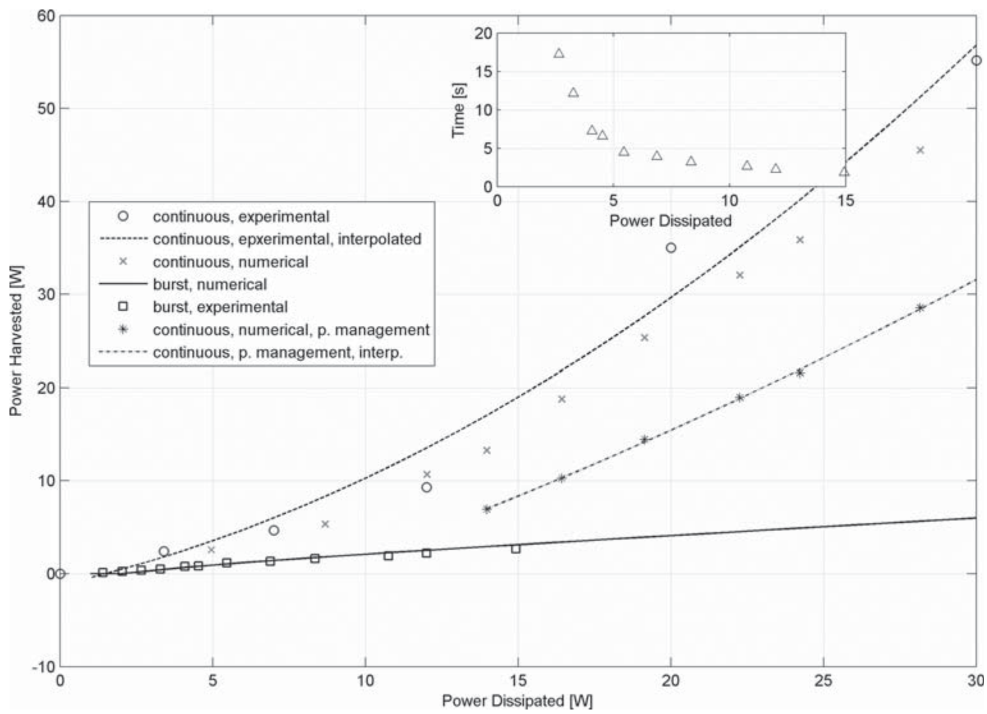

Fig. 6. Theoretical harvested power level with respect to the power dissipated in a bearing during the continuous operation mode (circles) and periodic operation 0.05 s (squares); The simulated (solid line) and measured power (squares) harvested in continuous operation with a step-up converter and power management unit; The simulated (dot-dashed line) and measured power (stars) in continuous operation with a step-up converter and MPP control. The minimum cycle length (triangles, nested graph) determined by experiment.

That is sufficient in practice of bearing monitoring installations. At the same time the availability of the shunted system would be between 1.5–5% of time in the case of LTC3108, which again can be perceived as the system capabilities in most unfavorable conditions. It is hard to assess the performance of the proposed method while powering the periodically operating shunt circuitry as the time intervals between the active and passive state remains unknown in opposition to monitoring devices. The in situ tests are necessary and are planned as a logical continuation of the present work.

7. CONCLUSIONS

The new concept of a semi passive piezoelectric vibration damper powered via a thermoelectric source has been proposed. The main idea behind the proposed solution involves turning the shunting circuit containing at least one synthetic inductor passive by delivering supply by means of power harvester that operates on a bearing. The approach allows the shunted piezoelectric to operate in favorable conditions as the synthetic inductor's resistance may be an order of magnitude lower than those of a typical coil inductor. The practical issues that are tackled by combining the shunt damping technique and energy harvesting are: making the shunt damping treatment operating independently of the power source; the energy is harvested where it is actually used eliminating the need for cabling. The concept has been proved experimentally by comparing the power consumption of synthetic inductors to the figures measured during the operation of a simple harvester. It was stated that a typical bearing during a typical working condition may be a sufficient source for the energy harvester to operate. Nevertheless, several questions have to be raised when designing a self-sufficient system: is the transition through the resonance in the machine run-up an important issue? and should the system be ready to operate since the beginning of the machine operation? If answer to any of these questions is positive the thermoelectric harvesting unit should be appropriately oversized in order to assure the energy excess that can be driven to the energy buffer during normal operation of the machine and therefore be available at the next start-up.

There is a great interest in passive damping methods that can substitute the usually used viscoelastic materials, especially because of the inability of the latter to adjust to the changing operational conditions and large temperature dependency of their performance. Shunted piezoelectrics proved the desired efficiency in the laboratories throughout the worlds, nevertheless the practical implementations suffer due to usually large inductance values needed in order to damp the structural vibrations (the lower frequency of the vibrations, the higher inductance value needed). Possibility of powering the synthetic inductors by energy generated from thermal gradients cause the piezoelectric vibration dampers to be more versatile in use and less bulky to implement.

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