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POWER HARVESTING IN A HELICOPTER LAG DAMPER

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ABSTRACT

Currently the lifespan of rotor blades is determined based on a conservative lifetime calculation. This leads to blades being discarded while they still possess a significant residual amount of flight-hours. Blade health monitoring systems are desired to actively track the strains in the blade thereby drastically extending the technical life expectancy. A major drawback is in the need for an electrical infrastructure to transmit all the signals to and from the rotor hub to aircraft body. It would be advantageous if the required power could be generated locally.

Within the European Clean Sky project vibration-based power harvesting is chosen as a solution to powering in-blade health monitoring systems. In this paper a new power harvesting application is developed and simulated. Local generation of power will allow for a 'plug and play' rotor blade and signals may be logged or transmitted wirelessly to the body of the aircraft. Examples are the blade strains, hinge forces, vibrations and so on.

The lag damper is chosen to be modified as it provides a well defined loading resulting from the regressive damping characteristic. Additionally the lag damper is designed to dissipate energy where such a system will instead recover the energy and use it purposefully. A piezo electric stack is installed inside the damper rod, effectively coupled in series with the damper. In typical harvesting applications the piezo element is designed to cope with the worst case scenario but generally operates far below this level. Due to the well defined peak force generated in the damper the worst case and operating scenarios are quite similar allowing the stack to be operated at maximum efficiency.

Development and simulation of the model is described starting with a simplified blade and piezo element model. Presuming specific flight conditions transient simulations are conducted using a chosen power harvesting circuit. Based on analysis the circuit is further optimized to increase the specific power output. Optimization of the electrical and mechanical domains must be done simultaneously due to the high electromechanical coupling of the piezo stack. This implies that the electrical aspects of the stack have a measurable influence on the mechanical domain and vice-versa. Where active circuits can affect rapid changes in voltage, the stack will respond in kind potentially inducing additional vibrations or reducing the harvesting efficiency. Such events must be prevented.

The dynamics of the rotor system must also be preserved. The high electromechanical coupling of the piezo electric system may lead to undesired vibrations being introduced in to the rotor. Simulations show that well designed systems have minimal effect on the force developed by the damper. On the other hand poorly designed systems may cause impulses with a force amplitude of nearly half of the standard lag damper.

A brief investigation is also done towards some nonlinear phenomena of the piezo electric material. The capacitance of the material for instance can show significant change with the voltage field and mechanical stress present in the material, reducing the output of the system.

From the numerical investigation the power harvesting lag damper seems to provide sufficient power for extensive health monitoring systems within the blade while retaining the functionality and safety of the standard component. The simulations show that for the 8.15m blade radius and 130 knots flight speed under consideration over 7 watts of power may be generated from a single damper.

This amount of power is more than sufficient to power *resistive strain gauges requiring micro- to milliwatts per measurement and short range wireless transmitters requiring in the order of one hundred milliwatts for continuous transmission. Within the near future 7 watts may even be within the capabilities of fibre-optic measurement systems. The power harvesting lag damper presents a viable and minimally invasive solution to powering rotor-based health monitoring systems. These monitoring systems will then aid in increasing the technical lifetime of rotor blades and reducing maintenance costs. Rotor blades will then be discarded when they are truly at the end of their technical lifespan.*

INTRODUCTION

Helicopter rotor blades are critical components of a rotor craft and structural integrity is paramount for the safety of the vehicle. Generally these blades are replaced based on a highly conservative lifetime calculation. The ability to extend the life of these blades would allow for a significant reduction in running costs as well as decreased environmental impact. Increasing the technical lifespan of the blade will require health monitoring systems to be installed which can keep track of the mechanical loads imposed on the rotor blades. With actual strain data residual lifetime calculations may be performed regularly and the blades can be replaced when they have truly reached the end of their technical lifespan.

A major challenge with such systems is providing sufficient and stable power. Within the European Clean Sky program a number of options have been explored. An inductive generator positioned around the rotor has been deemed unsuitable due to alignment requirements between rotor and body. Slip rings bring high maintenance and an unstable power supply. Power harvesting is also under consideration as an alternative and it will show to be a viable option.

Piezo electric material is investigated here as a source of power. When stressed this electrically poled material generates a charge difference between the electrodes. This material has traditionally been used for sensing and actuation purposes. In the past decade however research has been done to use it for powering small electrical systems. The generated charge is then conducted through an electrical circuit designed to maximize the power flow from the piezo element to an electrical load.

A suitable location must be found for the material where it will experience dynamic strain. The envisaged application is within a helicopter lag damper: a device which dampens in-plane blade oscillations in rotor craft in order to suppress air and ground resonance. Piezo material can be utilized in two ways: plates or stacks. Plates are well suited for most applications due to the low added stiffness and intrinsic stress amplification while stacks require high direct loading which is rarely possible [1]. The concept is unique in that it utilizes a directly excited stack which is possible due to the high 9kN force available [2]. Figure 1 shows an external view of a typical lag damper and a sectional view of the concept.

On the electrical side a harvesting circuit must be selected. The circuit extracts the charge generated by the piezo material and different circuits may yield wildly varying outputs. A considerable amount of research has been done towards optimal circuits which boost the power output. Examples include the 3 following similar techniques of voltage biasing [3], feeding energy back in to the patch to increase output [4] and the Synchronized Switch Harvesting on Inductor (SSHI) circuit [5], and other active circuits such as Synchronized Electric Charge Extraction (SECE) [6]. The choice has fallen upon the SSHI circuit as it may provide significant benefits over other circuits, mainly due to the non-resonant operation of the system [9]. Ideally up to a tenfold increase in output may be achieved over passive circuits.

The power harvesting device must not interfere with vehicle stability and safety. A drawback of the circuit considered in this paper are the mechanical oscillations resulting from the harvesting circuit rapidly changing the stack voltage. In this case however they are quickly damped out due to the very high damping of the mechanical system. The final goal of this study is to establish how much power can be harvested from such a lag damper system.

First modeling of the blade and piezo electric device will be discussed. A short overview of the electric circuit will be given as well. A number of important aspects relating to system design will be addressed. Then some results of an optimized configuration will be presented. The paper concludes with discussion of the results, effects on the rotor craft and some basic health monitoring power requirements and finally a conclusion.

1 MODELING

The lag damper is designed to suppress air- and ground-resonance. These phenomena result from the coupling of aerodynamics and structure dynamics. Since this en-

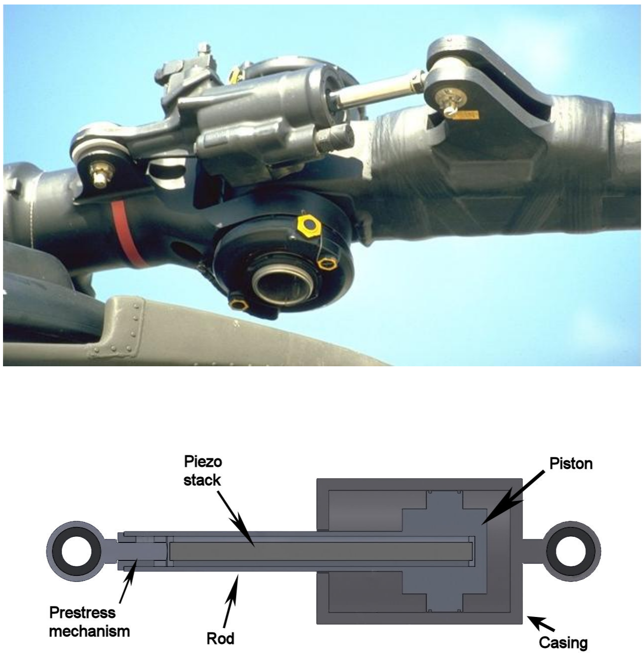

Figure 1: Lag damper external view (above) and power harvesting concept (below)

ergy is otherwise dissipated as heat it provides an efficient excitation. A piezo electric stack is installed inside a hollow damper rod. A pre-stress mechanism is added to prevent tensile forces on the stack as the material is very brittle. A design outline is shown in Figure 1.

The lag damper is taken from a generic rotor with an 8.15m radius [2]. The flight condition under consideration is straight and level flight, with a velocity of 130 knots (66.9m/s). For these conditions the developed damper force F_0 resembles a step function with a 9kN amplitude with a frequency identical to that of the rotor speed Ω =4.18Hz. The rotor speed is the dominant frequency that the damper is subjected to. The force F_0 is a built-in limit in the damper and is reached during forward flight, presenting a consistent and prevalent excitation. The associated force-velocity profile is given in 2.

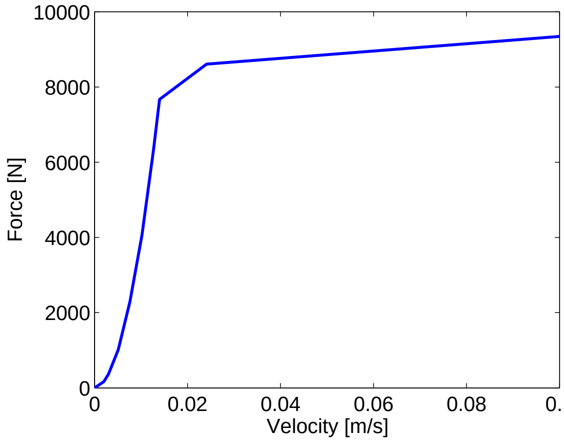

Figure 2: Lag damper velocity-force profile)

1 Mechanical model

Using data provided by *Agusta Westland Helicopters* (AW) it can be determined that a 1 degree of freedom (DOF) model is acceptable for the blade. Figure 3 shows results from *AW* simulations and the 1DOF blade and standard damper model. The damper velocity matches reasonably well but the insensitivity of the force above 0.02m/s allows for an acceptable approximation, see figure 3.

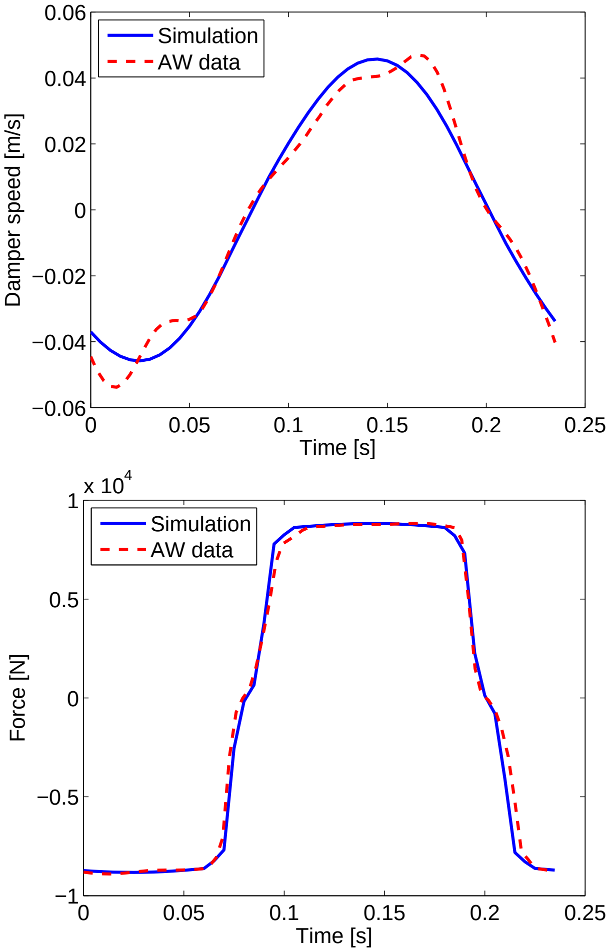

Figure 3: Lag damper velocity (above) and force(below), simulation (solid) and *AW* data (dashed)

The stack also possesses one DOF in the form of displacement. The damper and stack are in series and the excitation of the stack is generated by the velocity change in the damper. The final 2DOF model for power harvesting is shown in figure 4. It shows the blade represented by 1 DOF with moment of inertia J, excitation moment M_0, an equivalent rotary spring k_{eq} to represent the centrifugal stiffening effect at constant rotor speed, the lag damper, piezo electric stack with DOF u and a mass M representing the piston. The excitation moment is chosen such that the model and *AW* data yield the same amount of dissipated energy (245W) and is 10.7kNm.

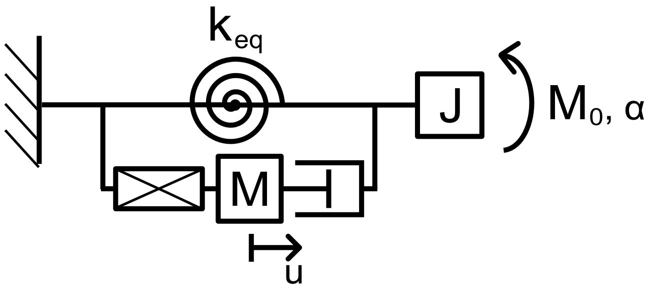

Figure 4: Lag damper harvester ideal physical model

For the stack the maximum permissible dimensions within the damper rod are 20mm in diameter and 0.25m in length. A shorter stack is of course possible but for the sake of determining the maximum achievable output the largest dimensions are assumed.

1 *Electrical model*

The piezo electric element is modeled using the following equations:

$$k_p u(t) + \theta V_p(t) = F(t) \tag{1a}$$

$$\theta \dot{u}(t) - C_p \dot{V}_p(t) = I(t) \tag{1b}$$

With stack short circuit stiffness k_p, displacement $u(t)$, electromechanical coupling θ, piezo voltage $V(t)$, external force $F(t)$, capacitance C_p, and outgoing current $I(t)$. The short circuit stiffness k_p capacitance C_p and electromechanical coupling θ of the stack are calculated as:

$$k_p = \frac{E_{33}A}{L_s}, \qquad C_p = \frac{\varepsilon^{\sigma} nA}{t_l}, \qquad \theta = \frac{e_{33}A}{t_l} \tag{2}$$

With n representing the number of layers in the stack and L_s the total stack length. The layer thickness t_l will later be varied to investigate any influences on the performance of the circuit.

The PIC181 material is chosen in this simulation. It is a 'hard' lead zirconate titante (PZT) material meaning it is stiffer and can handle higher voltages than 'soft' materials. Material data is given in table 1. Based on the maximum material stress the cross section can be determined as $1.5 \cdot 10^{-4}\text{m}^2$. This is based on a compressive force of 18kN, twice the amplitude of the lag damper due to the stack being pre-stressed to 9kN.

Table 1: Material data PIC181 (PICeramic)

Density ρ	7800	kg/m^3
Youngs modulus (1D stress) E_{33}	71	GPa
Piezo electric coefficient e_{33}	14.7	N/Vm
Relative permittivity ε_r^{σ}	1200	-
Max stress σ_{max}	120	MPa
Max reverse bias E_v (room temp)	10^6	V/m
Curie Temperature T_c	330	°C
Coupling k_{33}	0.66	-

The Synchronized Switch Harvesting on Inductor (SSHI) circuit [5] is used to extract the electrical energy from the stack. Based on [7] the use of the SSHI circuit in a non-resonant system allows for a significant increase in output over other known circuits. Figure 5 shows the circuit with the piezo element (current generator and capacitance C_p), a switched inductor L (switched with MOSFET with gate voltage V_g), the diode rectifier, storage capacitance C_s and resistive load R.

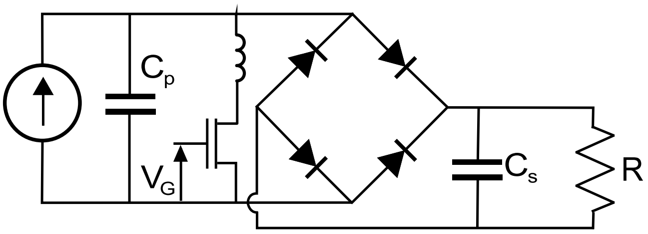

Figure 5: SSHI circuit schematic

SSHI utilizes a switched inductor coupled with the stack capacitance to create an electrical oscillator. Upon displacement extrema the inductor is switched on for half of one period allowing the voltage to change polarity from $+V_{dc}$ to $-V_{dc}$ and vice versa. This is shown in figure 6 along with the stack displacement $u(t)$ for clarification (note the figure assumes negligible electromechanical coupling). This inversion must happen quickly enough to avoid a significant change in force and/or displacement on the stack which would reduce power output. The current is conducted away from the piezo element via a diode rectifier to a storage circuit. The voltage V_{dc} in the storage circuit remains nearly constant due to the large storage capacitor C_s. A more detailed description of its operation and governing equations is given in [5] and a detailed analytical account is given in [8].

The inductor adds a parasitic resistance which is accounted for using the inductor quality Q_i. A higher value of Q_i indicates lower electrical losses. From [8] it is shown that the SSHI circuit possesses an optimal resistance value, written as:

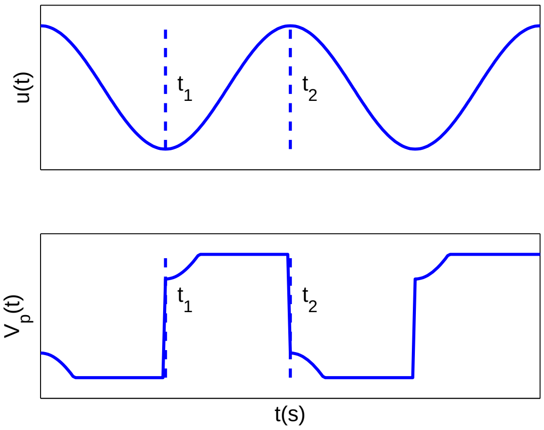

Figure 6: SSHI displacement (above) and stack voltage (below) waveforms

$$R_{opt} = \frac{\pi}{C_p\left(1 - e^{\frac{-\pi}{2Q_i}}\right)\omega} \tag{3}$$

Again, the stack cross section is chosen based on the applied mechanical load. Due to the resulting high stress this optimum resistance will drive the voltage up beyond the maximum reverse bias, thereby damaging the material. Rewriting equation (20) from [8] and assuming a low frequency excitation compared to the mechanical natural frequency of the piston mass on the stack ($\Omega \ll \omega_{mech}$) the following equation is found yielding the maximum resistance R as a function of the maximum voltage field $V_{p,max}$, excitation force F_0 and stack properties k_p, C_p and θ:

$$R = \frac{-V_{p,max}\pi k_p}{\Omega\left(2F_0\theta - V_{p,max}\left(1 - e^{\frac{-\pi}{2Q_i}}\right)\left(\theta^2 + k_pC_p\right)\right)} \tag{4}$$

Another issue concerns the capacitor-inductor oscillator. For low coupled systems the inversion duration adheres to that of the electrical domain only. The associated natural frequency is written as $\omega_{el} = 1/\sqrt{LC_p}$. Here the high coupling implies that the full electromechanical equations must be solved to find the optimum inversion duration. Moreover the very high damping resulting from the lag damper (ζ=0.75) must be taken into account. This value of ζ is only valid for $\dot{u} > 0.02m/s$, below this velocity the blade is super critically damped. For the inversion process alone a linear system can be assumed. Note that operation of the damper is also assumed linear, implying the velocity remains above 0.02m/s as according to figure 2. The damping coefficient for the final linear portion above 0.02m/s is C=9700Ns/m. Solving the 3DOF system (blade angle α, stack displacement u and voltage V_p) is not necessary as the inertia of the blade is sufficiently high. The following 2DOF equation (u and V_p) is solved yielding the natural frequency ω_{em} of the electromechanical oscillation:

$$\begin{bmatrix} M & 0 \\ 0 & C_p \end{bmatrix}\ddot{q} + \begin{bmatrix} C & \theta \\ -\theta & R_L \end{bmatrix}\dot{q} + \begin{bmatrix} k_p & 0 \\ 0 & \frac{1}{L} \end{bmatrix} q = 0 \tag{5}$$

with $\dot{q} = \begin{bmatrix} \dot{u} & V \end{bmatrix}^T$.

Lastly the inversion duration influences the efficiency of inversion. As indicated the high electromechanical coupling implies a response in the highly damped mechanical domain. Minimizing viscous losses requires as slow inversion as possible to reduce the velocity u. The incurred viscous losses are proportional to $\dot{u}^2$. Figure 7 demonstrates the difference between swift inversion and slow inversion. The horizontal axis shows the time normalized with the period of the respective oscillation, with a value of 1 indicating the moment where the electrical oscillator is switched off. The vertical axis shows the voltage normalized with the starting voltage. The solid line represents very quick inversion ($\omega_{em} \gg \omega_{mech}$) where initially the efficiency is better but as the mechanical domain (not shown) is excited and settles towards the new equilibrium a significant amount of energy is lost. The dashed line represents very slow inversion ($\omega_{em} \ll \omega_{mech}$) where the electromechanical frequency is chosen much lower than that of the mechanical domain. The mechanical DOF follows almost immediately and slowly minimizing viscous losses.

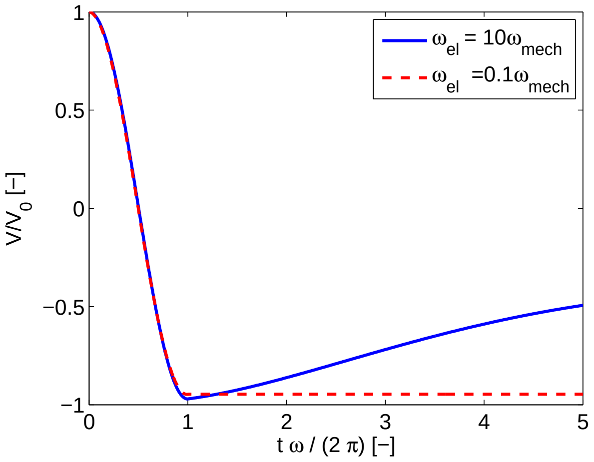

Figure 7: Voltage vs. normalized time for fast (solid) and slow (dashed) inversion

2 RESULTS

A *MATLAB / Simulink / Simscape* model is made according to the model described in section 1. The optimal parameters for the model as given in table 2 are used. The simulation is run for 100 rotor rotations after which a quasi-static state has been achieved. Figure 8 and figure 9 show the dissipated power starting from a discharged state and the voltage and current waveforms of the stack and through the rectifier. From the current waveforms the moment of inversion can be observed where it peaks to 3A. The wider 0.5A peak is when the element is conducting through the rectifier to the storage capacitor. The voltage asymptotically approaches 60V, which is also the maximum reverse bias, showing excellent agreement with equation 5. Here the moment of inversion is signified by the sharp changes from positive to negative and vice versa.

Table 2: Simulation parameters

Stack stiffness k_p	$4.26 \cdot 10^7$	N/m
Stack capacitance C_p	$8.38 \cdot 10^{-5}$	F
Electromechanical coupling θ	36.7	N/V
Load resistance R	471	Ω
Inductor quality Q_i	100	-
Inductance L	$43.3 \cdot 10^{-3}$	H
Storage capacitance C_s	$8.3 \cdot 10^{-3}$	F
Blade moment of inertia J	2387	kgm^2
Equivalent hinge stiffness k_{eq}	$1.44 \cdot 10^5$	N/rad
Blade moment amplitude M_0	$10.7 \cdot 10^3$	Nm
Piston weight M	1	kg
Lag damper mounting distance r	0.254	m
Rotor speed Ω	4.18	Hz
Stack section area A	$1.5 \cdot 10^{-4}$	m^2
Layer thickness t_l	$6 \cdot 10^{-5}$	m
Stack length L_s	0.25	m

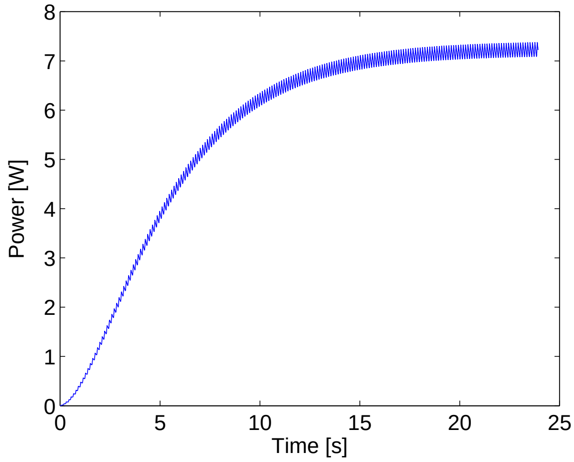

Figure 8: Power output vs. time

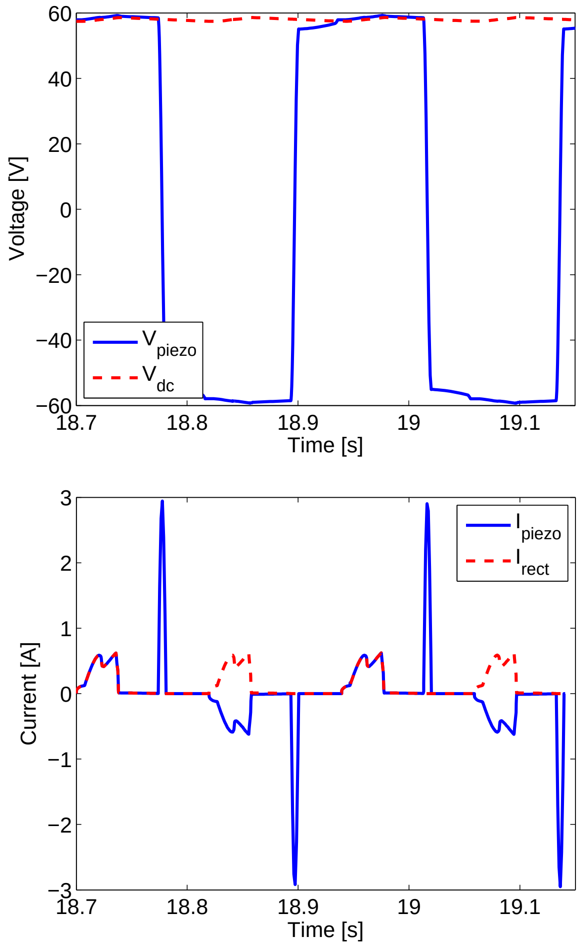

Figure 9: Piezo (solid) and rectified (dashed) voltages (top) and currents (bottom)

Due to the high coupling an impulse may develop in the lag damper upon inverting the stack voltage. Figure 10 shows that for the optimized SSHI circuit this force variation is 2.3% of the peak force (solid line). On the other hand a poorly designed circuit may lead to impulses in the order of 3kN, or over 30% of the peak loading (dashed). This is related to how quickly the stack voltage is inverted where slower inversion induces a lower impulse.

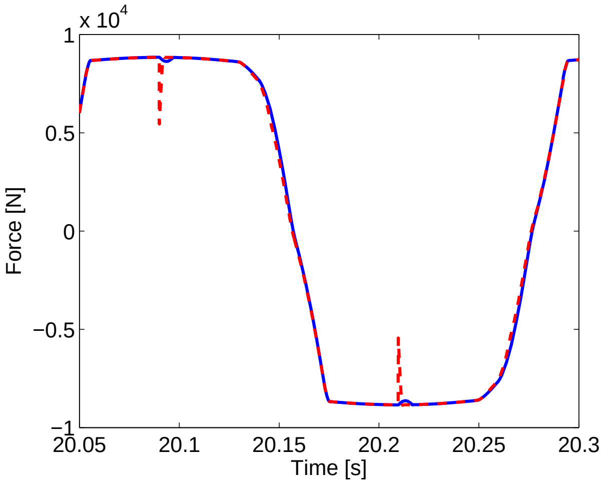

Figure 10: Damper force vs time for well (solid) and poorly (dashed) designed circuits)

3 DISCUSSION

Simulations show the optimized lag damper power harvester will yield 7.3W of power. The limitation to this result is that non-linear effects [9] and temperature effects are not included. The first will result in a reduction in harvested power due to larger losses during voltage inversion. The increasing capacitance leads to more charge stored in the capacitance C_p which must be transferred during inversion. More charge implies higher currents and larger resistive losses. It is expected that the loss may be limited by increasing the load resistance.

Increasing ambient temperature decreases the maximum reverse bias, thereby decreasing the power output, with the Curie temperature representing the limit where no power is harvested. The system must be designed to withstand temperatures from -40 to 70°C, making the higher temperature the limiting factor. Data from PICeramic indicates roughly a 20% decrease in the maximum reverse bias at 70°C and therefore a 35% decrease in power (considering that $P = V^2/R$). Considering the capacitance increase and temperature requirements the output is estimated to reduce to around 5W.

The stack used here is quite large and in combination with the long inversion time and the associated large inductance this forms a practical limit. In this particular case the inductance has a value of 50mH and must handle 3A of current. Such a coil will weigh in the order of a kilogram. The viscous losses which are incurred are proportional to the square of the velocity: $\dot{u}^2$. A shorter stack or more creative solutions such as dividing the stack in two segments and inverting the voltage sequentially will quickly alleviate this problem altogether.

Health monitoring systems require a small amount of power. For instance [10] present a strain gauge which consumes only 14μW of power to perform strain measurements. Also, *Microstrain* brand wireless strain and 2-axis acceleration measuring systems consume 0.1-0.5mW and 1mW respectively. Short range wireless transmission requires in the order of 100mW peak power. Fibre optic measurement systems currently consume in the order of 20W of power, however manufacturers are striving to reduce the power consumption. In the future the amount of harvested power may lie within the requirements of FO measuring systems. A single optical fibre is capable of transmitting 16 strain signals per fibre @2,5kHz measuring frequency (Smart Fibre - Smart Scan measurement system). Compared to resistive strain gauges which require two wires each, embedded fibre bragg gratings and optical fibres will simplify blade strain measurement systems in the more distant future.

The flight characteristics of the aircraft must also be preserved. With the lag damper present-ing a critical component the harvester may not influence its operation. First, the force exerted by the lag damper must not change. Simulations show that a poorly designed circuit will induce impulse loads in the lag damper of over 30% of the maximum force during normal operation. When properly designed these forces are limited to 2.3%. No full dynamic simulations including the aircraft have been performed with respect to stability changes in the aircraft. Since the total amount of dissipated power in the power harvesting lag damper is higher than the lag damper alone (254W vs 245W) it is not cause for major concern in this phase of investigation.

Lastly the harvester must not jeopardize the safety of the rotor craft if the system fails. Failure of the electronics does not cause any mechanical problems as the piezo will be dead weight. On the other hand, failure of the piezo material may cause problems. These can be minimized by ensuring that the piezo material fits loosely but snugly in the rod of the damper. If the material should then fail it may still provide support for the lag damper.

Other flight conditions have not yet been considered. However considering figure 2 it is a reasonable assumption that for slower speeds the amount of harvested power will be very similar until the reduced flight speed causes the peak damper velocity to decrease below 0.02m/s.

4 CONCLUSIONS

A power harvesting system for the rotor of a helicopter is presented and simulated. The simulation shows that up to 7.3W of power can be harvested from a single lag damper during horizontal flight. This is sufficient to power countless measurement nodes in the blade. The simulation does not take two important non-linear effects into account although their effect is discussed qualitatively. Including these two effects will lead to an expected output of about 5W. If the health monitoring system in the blade requires less energy the length of the stack can be decreased to match.

Also some new design issues with respect to the SSHI circuit have been explored when it is used in a strongly coupled system. The natural frequency of the voltage inversion must be solved using the coupled electromechanical equations of motion and the influence of high mechanical damping is discussed as well.

The system is expected to have minimal influence on the dynamic stability of the helicopter and the mechanics of the lag damper. In case of failure of the harvesting system the safety of the aircraft is not compromised.

5 ACKNOWLEDGEMENTS

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