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Validation of optimised vibration energy harvesters under near operational conditions

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Abstract

Aircraft structures and systems are commonly exposed to mechanical loading with high-frequency and stress. These harsh operating conditions reduce the integrity of aircraft structures over their operational life-cycle, requiring routine maintenance checks. Such checks can incur a significant penalty in aircraft availability and fleet capability. On-board autonomous sensors that monitor the health of the structure can be utilised to minimise the number and, hence, impact of maintenance checks on the availability and capability of the aircraft. Powering these on-board sensors can be difficult, since they are often inaccessible and, thus, cannot be powered locally or by batteries. However, the aforementioned high-frequency environment can be utilised to power the on-board sensors through the use of energy harvesters. Recently, optimised vibration energy harvesters tuned to the meshing-frequencies of a Bell 206B-1 Kiowa helicopter main rotor gearbox were reported. The harvesters were based on relaxor ferroelectric single crystal (RFSC) transducers. The optimised devices were experimentally validated using an electro-dynamic shaker, under laboratory conditions and at room temperature. However, if the full potential of these devices is to be realised, then their ability to generate power in an environment that is representative of the operational conditions for an aircraft is required. To this end, several gearbox-vibration harvesters have been precision-manufactured from spring-steel sheets using electric discharge machining (EDM) wire-cutting. Aluminium brackets for mounting the harvesters were designed with eigen-frequencies outside the range of gearbox-meshing frequencies. This paper reports on the laboratory analysis of the harvesters was performed with aim of determining the power generation capabilities of the RFSC-based energy harvesters under operational temperatures.

Keywords: vibration energy harvesting, helicopter gearbox, broadband energy harvesting.

Introduction

Health sensing systems on aerospace vehicles can provide valuable ongoing assessment of internal components and their capability, enabling health and usage monitoring and condition based maintenance through continual tracking of weak-points and minimising the need for disassembly [1]. While these sensor systems are useful, implementation into aerospace vehicles can be difficult, with manufacturers restricting access to onboard power sources. Using batteries as an alternative requires frequent replacement or recharging, each time necessitating dismantling of the vehicle, which negates the convenience and practicality offered by the sensor systems themselves. Instead, an energy harvesting device which uses the mechanical vibrations that an air vehicle produces may be used to power a health sensing system [2]. The driving accelerations for these harvesters can vary from low-frequency manoeuvre loads to high-frequency accelerations associated with transmission meshing frequencies. A device can thus be tuned to one or more of these frequency components, converting the vibrational mechanical energy into useable electrical energy to power the sensor systems.

A well-studied method of transduction is through piezoelectric-based vibrational energy harvesting. In the current literature, third generation manganese-doped Relaxor Ferroelectric Single Crystals (RFSC) ($Pb(Mg_{1/3}Nb_{2/3})O_3{-}Pb(Zr,Ti)O_3$(Mn−PMN−PZT) [011]) (hereafter Mn−PMN−PZT) have been used for energy harvesting. A recent paper has demonstrated crystal power densities of up to 85.7 W/cm^3 [3], five to ten times greater than that produced by traditional sintered piezoceramics [4, 5]. The performance of the RFSC-based "topology-3" harvester, discussed in reference [2], was maximised by using a combination of the more effective third-generation RFSC transducers and an optimisation process to align the resonant frequencies of the device with environmental conditions. This paper investigates the response of the "topology-3" harvester when operating under the operational temperatures of a helicopter transmission.

The "topology-3" harvester, which consists of a topology optimised spring-steel cantilever beam with a pair of RFSC [011] poled disk transducers, is designed to harvest from multiple high-frequency vibration components associated with a helicopter transmission [2]. The "topology-3" was based on a cantilever that was tuned to multiple prominent gear meshing frequencies (1900 Hz, 2250 Hz, 2500 Hz) of a Bell 206-B Kiowa Helicopter main rotor transmission, and was designed through the use of a topology optimisation algorithm through a process known as Bi-directional Evolutionary Structural Optimisation (BESO) [2]. The "topology-3" is a unique multimode kilohertz harvester that produced a maximum 3.1 mW when driven at $2g$ (where g is 9.81 m s^{-2}). For comparison, a recent review of the literature [6] detailed a cantilever beam of similar volume (10 mm x 40 mm x 0.5 mm) [7] to produce 1.04 to 1.97 mW of power using a PZT based transducer, though the device had a resonance frequency of 8.79 to 8.83 Hz. The review paper only describes one cantilever beam operating in the kilohertz range, which produced 8 µW from a resonance of 1110 Hz [8].

A recent study by the authors [9] found that the "topology-3" harvester was extremely sensitive to the quality of manufacturing. It was found that certain "topology-3" manufacturing errors lead to large measured differences in the resonant frequencies compared to the designed, which lead to a sub-optimal energy yield. This paper aims to rectify these manufacturing errors, with a focus on the "topology-3" mounting arrangement. As will be discussed, the validity of this new arrangement was demonstrated through laboratory experiments, showing that the "topology-3" harvester can be designed to resonate at the three designated frequencies, within experimental error. Once validated, the "topology-3" was subjected to a range of temperatures that are reflective of the operational environment and the impact of temperature quantified. A multi-physics electro-mechanical model is then developed and compared to the laboratory measurements, to validate the predictability of the numerical model.

Modelling

As mentioned, the "topology-3" harvester is the focus of this study. The harvester consists of a spring-steel (AISI 1095) cantilever beam and two bonded Mn-PMN-PZT disk transducers of diameter 6.35 mm and thickness 0.5 mm. material properties of the transducer are reported in [10, 11]. The spring-steel is assumed to have a Young's modulus of $E = 205$ GPa, a Poisson's ratio of $\nu = 0.3$ and a density of $\rho = 7850$ kg m^{-3} [12]. The model includes a silver-loaded epoxy bond line between the transducers and the beam, which is approximately 0.2 mm thick. The room temperature epoxy material properties have been taken from [2]. The variation in the epoxy Young's modulus with temperature is measured in this study by applying a load to an epoxy specimen and measuring the resulting strain at various temperatures.

As mentioned earlier, the spring-steel cantilever was designed using a BESO algorithm [13]. The algorithm determined the topology of the cantilever beam such that the "topology-3" harvester is tuned to the meshing frequencies of the helicopter gearbox. More details of the multi-physics modelling used to design the "topology-3" harvester can be found in [2]. To optimise the orientation of the transducer disks, the modal participation factor for the modes of interest were maximised. The modal participation factor determines how strongly a given mode contributes to the response of the structure when subjected to a given excitation. Therefore, it is reasoned that the larger a given mode's contribution to the structural response, the more that mode can be excited and hence the more electrical energy can be produced from exciting it.

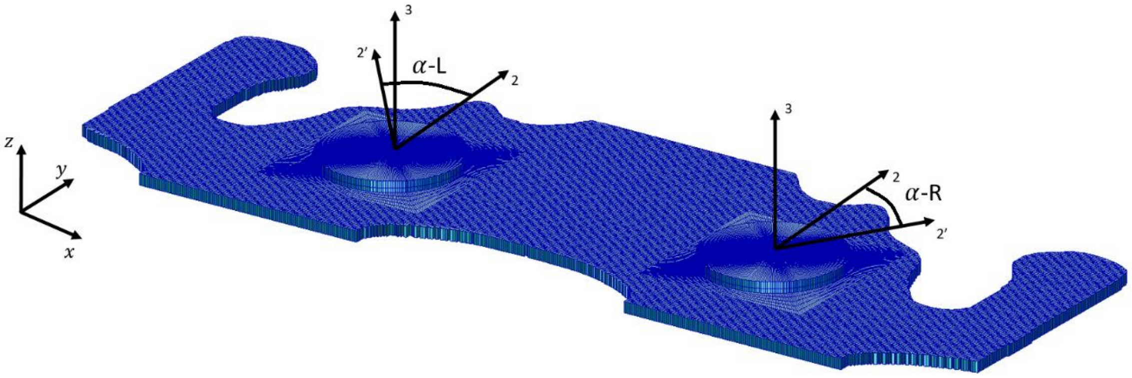

Fig. 1: Multi-physics model of cantilevered energy harvester constrained along the lower edge (designated as the root). RFSC transducer disks are shown with their respective piezoelectric co-ordinate frame, where 2' represents the 2 axis after rotation (i.e. α-L and α-R). Disks separated from spring-steel beam by 0.2 mm thick bond line of silver-loaded epoxy.

As the mechanical properties of the RFSC disks are anisotropic, varying the orientation of the disks (shown in Fig. 1) alters the participation factor of a given mode. The optimum orientation of the two transducers, i.e. the angle pair (α-L, α-R) shown in Fig. 1, was found by stepping through the modelled α range of ± 90 °with 5 °increments, i.e. 37 x 37 = 1369 total models. The trade-off space for the participation factors of interest could then be determined. The optimum orientation combination for the two transducers was determined to be (α-L, α-R) = (-25°, +25°), which maximised the participation factors of interest, this combination was then selected from the trade-off space.

Experimental

This section describes the assembly process for the "topology-3" harvester, including the electrical discharge machining (EDM) wire cut spring-steel cantilever and bonding of the RFSC transducers. Experimental characterisation of the harvester, including electrodynamic shaker testing and impedance analysis, is also discussed.

Harvester Assembly

The cantilevered section of the topology optimised energy harvester was fabricated from 0.51 mm thick carbon spring steel (AISI 1095). The beam shape was precision-cut using an EDM wire cutter, with a machining accuracy of 0.1 mm. This is the first improvement made to the manufacturing process from the previous study [9], namely, significantly higher machining accuracy is achievable by switching to EDM wire cutting, compared with waterjet cutting. It was previously observed that the dimensions of the manufactured specimen deviated from the design specification, affecting the dynamics of the harvester [9].

The chosen transducers were relaxor ferroelectric single crystal disks [011] Mn−PMN−PZT (Ceracomp HPSC 200-145), with nominal piezoelectric charge constant d_{32} ~ -1100 pC/N and an electromagnetic coupling factor k_{32} ~ 0.8 [10]. Impedance sweeps (Solartron SI -1260) were conducted prior-to and after bonding the transducers to the cantilevered beam, and a d_{3j} meter (IACAS ZJ-6B) was used to determine the crystallographic direction of the disks in the method demonstrated in [11].

The piezoelectric disks were bonded to the cantilevered beam using silver-loaded conductive epoxy (Chemtronics CW2400) at positions of high stress predicted by modelling. As discussed in the previous section, the two transducers were oriented so that the ‘2 direction’ of the crystals was (α-L, α -R) = (-25°, +25°), maximising the output voltage for all three modes. Thin copper wires were bonded to the upper face of each transducer, and a ground path was formed through a bonded wire to the cantilever beam on the cantilever beam root (see Fig. 1).

The modelled “topology-3” harvester was tuned such that its first three natural modes had the frequencies of 1900 Hz, 2250 Hz, and 2500 Hz, respectively. Previous studies [2, 9] indicated that the method of mounting of the cantilever in the bracket was critical for avoiding spurious behaviour. In this study slots were added to the clamped section of the cantilever to avoid deformation of the bracket (see Fig. 2). One of the achievements of this work is to have a manufactured “topology-3” device that produces consistent results with the modelled harvester.

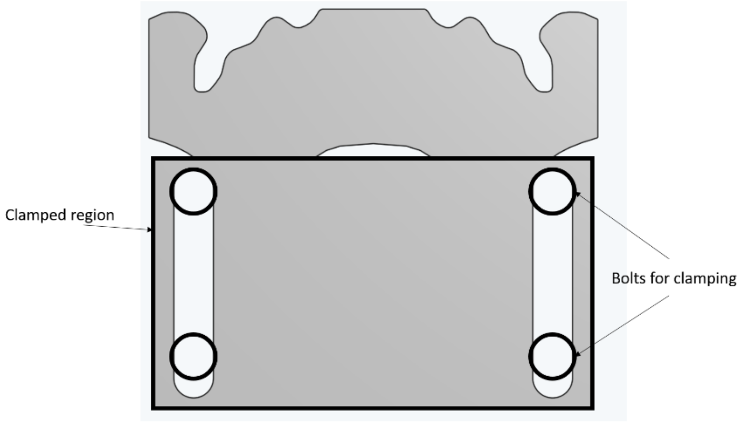

Fig. 2: Plan view of the topology 3 cantilever showing the addition of a clamped region to prevent deformation of the bracket.

Harvester Characterisation

The prototype “topology-3” harvester was mounted in an aluminium bracket for both impedance testing (Fig. 3 left) and electrodynamic shaker testing (Fig. 3 right). In the future, the same bracket will be used for attaching the harvesting device to the helicopter transmission. A torque of 4 N.m was used to secure the cantilever within the bracket. This torque was found to be well above the value needed to avoid impacting the dynamics of the harvester. For the shaker testing, the bracket was attached to a 1 kg host mass using double sided tape (3M XP6114) with a sinusoidal host acceleration applied in the vertical direction by an electrodynamic shaker (LDS ElectroDynamic Shaker – LDS V455). The electrodynamic shaker was driven by an amplifier connected to a loop controller (Bruel & Kjaer 7541). The host mass acceleration was 2.0*g* and the frequency range 1000 Hz to 3000 Hz, encapsulating the three modes of interest. Open circuit voltage from the device were recorded using an oscilloscope (Picoscope 6403) and 10 MΩ probes. This is done at room temperature to ensure the frequency response of the device is as intended.

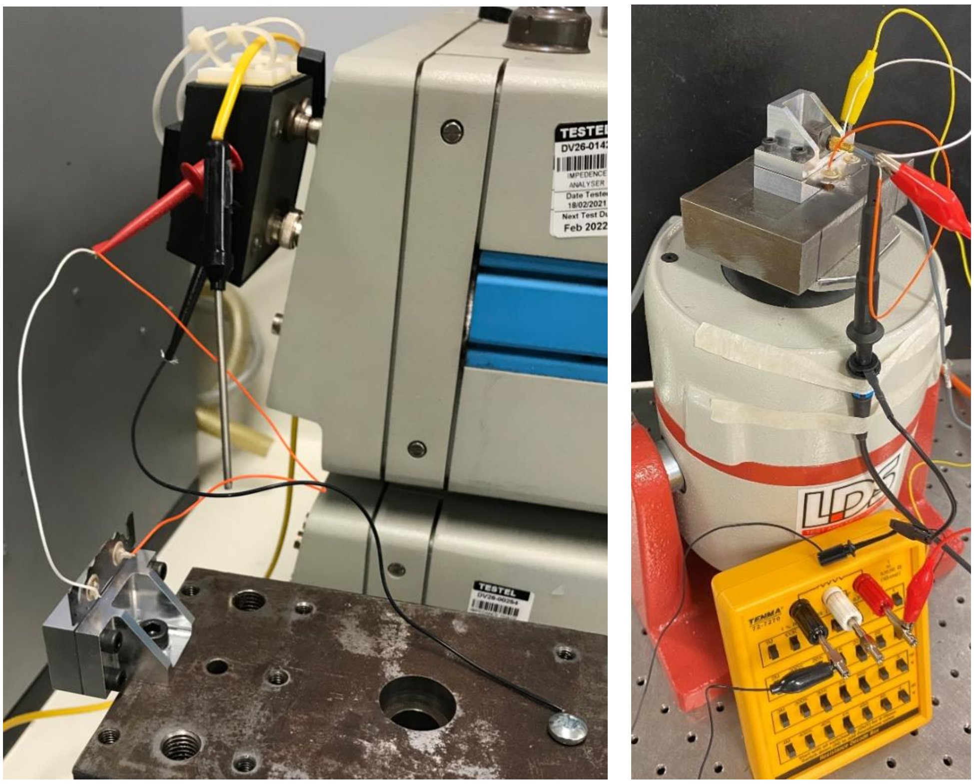

Fig. 3: Impedance analysis (left) and electrodynamic shaker analysis (right)

An impedance analysis is performed on the mounted device (Solatron SI-1260). The analysis was done at varying temperatures, beginning at room temperature (~20^{o}C) and increasing up to 90^{o}C to capture the complete operating range of the helicopter gearbox. This allows the effect the temperature has on the frequency response of the device to be quantified.

Results and Discussion

In this section, the “topology-3” model predictions and experimental findings are detailed. This includes the multi-physics modelling predictions for the effect of temperature on the dynamic behaviour of the harvester as well as the electrodynamic shaker and impedance analyser laboratory tests. In particular, the new manufacturing method and clamping arrangement are verified by comparing the room temperature frequency response on the shaker with the modelled response and the impact temperature has on the dynamic behaviour of the harvester is both predicted by the multi-physics model and measured in the laboratory using the impedance analyser.

Frequency Response Validation

First, to ensure the discrepancies seen between the measured “topology-3” harvester behaviour and the multi-physics model observed in [9] have been rectified, the device is mounted on an electrodynamic shaker and the output voltage from both the left and right disks were measured. The multi-physics model was then used to predict the open circuit voltage of the harvesting device. Figure 4 shows the results from the electrodynamic shaker and the corresponding modelled results.

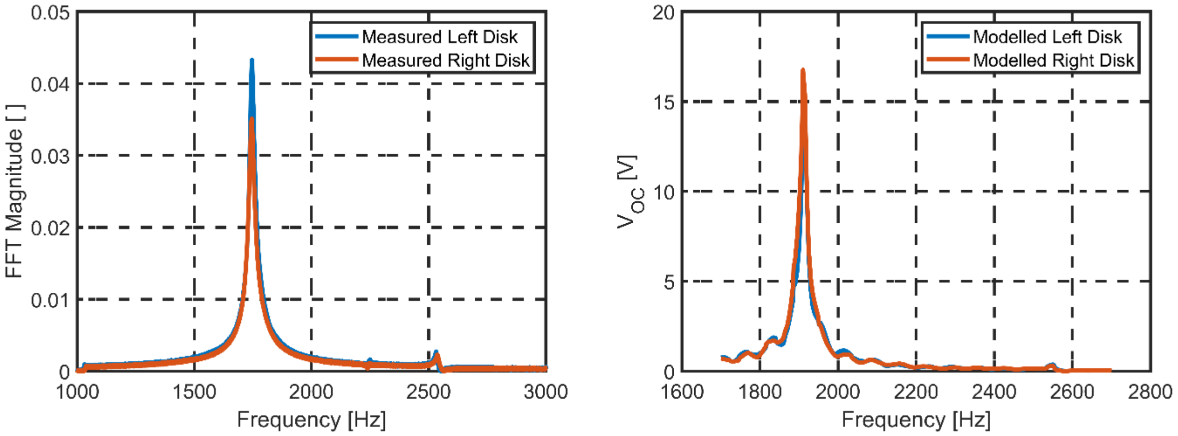

Fig. 4: Measured FFT response (left) and modelled open circuit voltage (right) for energy harvesting device as a function of frequency for a 2g RMS acceleration at room temperature

The three modes can be seen in both the left and right disk responses from the electrodynamic shaker (Fig. 4 left). The first mode has the largest magnitude, which corresponds to the largest power generation capability, which is congruent with the assumption that mode participation factor is proportional to power output. The first mode is recorded to be at a frequency of 1750 Hz, which is noticeably less than the 1900 Hz designed for, however, within the uncertainty bounds as reported in [2]. This is a significant improvement on the set-up reported in [9] and an indication that the new manufacturing process and clamp arrangement have alleviated the erroneous behaviour. The second mode is significantly smaller in magnitude than the first and has a frequency of 2251 Hz, close to the designed frequency of 2250 Hz. The third mode has a larger magnitude response compared to the second mode, but still substantially smaller than the first. The third mode has a frequency of 2530 Hz, again close to the designed value of 2500 Hz. The modelled response, shown in Figure 4 (right), is consistent with the measured response. These results indicate that the inconsistencies previously reported in [9] have largely been removed. Next, the effect of temperature on the dynamic response of the harvesters will be investigated.

Effect of Temperature on Frequency Response

The effect of temperature on the dynamic performance of the harvester is quantified to determine the expected degradation in performance when operating in the helicopter gearbox environment. The measured reduction in stiffness of the bond line with temperature is illustrated in Figure 5.

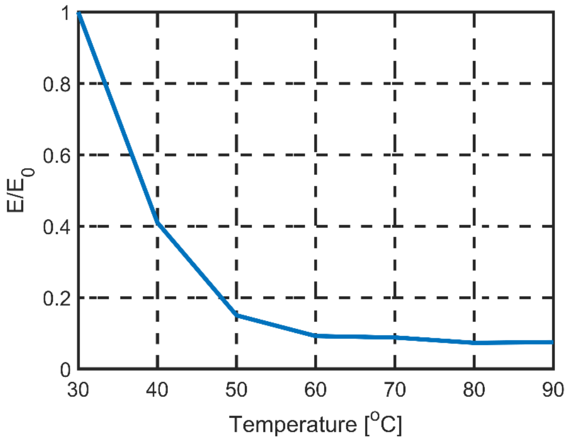

Fig. 5: Measured variation of bond line stiffness with temperature

Over the temperature range 30°C – 50°C, the bond line stiffness decreases from 100% of the room temperature stiffness (E_0) to 15% (Fig. 5). The stiffness then slowly reduces to approximately 7% of the room temperature stiffness as the temperature is further increased to 90°C. It is expected that this softening will have an impact on the dynamics of the "topology-3" harvester as well as the voltage generated.

The multi-physics model is used to predict the change in the "topology-3" harvester dynamics as well as output power characteristics. Figure 6 shows the predicted open circuit voltage of the harvester at various temperatures.

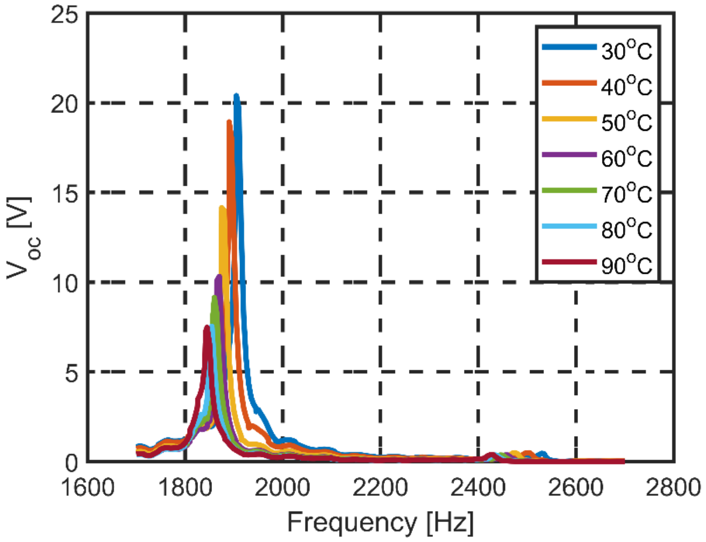

Fig. 6: Modelled open circuit voltage for the "topology-3" harvester as a function of frequency for a 2g RMS acceleration at different temperatures

As the temperature is increased the frequency of the modes decrease (Fig. 6). Furthermore, as the temperature increases, the open circuit voltage and hence power generation capability decreases (Fig. 6). The multi-physics model predicts the first mode to reduce by 52 Hz when operating at 90°C compared to 30°C. The reduction in open circuit voltage is predicted to be 12 V for the same temperature increase, which is about 60% of the room temperature value. The second mode is predicted to reduce by 89 Hz and the third mode is predicted to reduce by 135 Hz.

The reduction in the frequencies and open circuit voltage magnitudes is due to the softening effect of temperature on the silver-loaded epoxy bond line and spring-steel cantilever, i.e. as the temperature is increased the stiffness is reduced. The reduction in the open circuit voltage can be explained by the increased damping effect the bond line has on the transducer when it softens. As the bond line stiffness reduces, a smaller fraction of the load is transmitted to the transducer, resulting in lower stresses and hence lower output powers. To verify the accuracy of the model predictions, impedance analysis at various temperatures is performed on the manufactured device. Figure 7 shows the results of the impedance analysis.

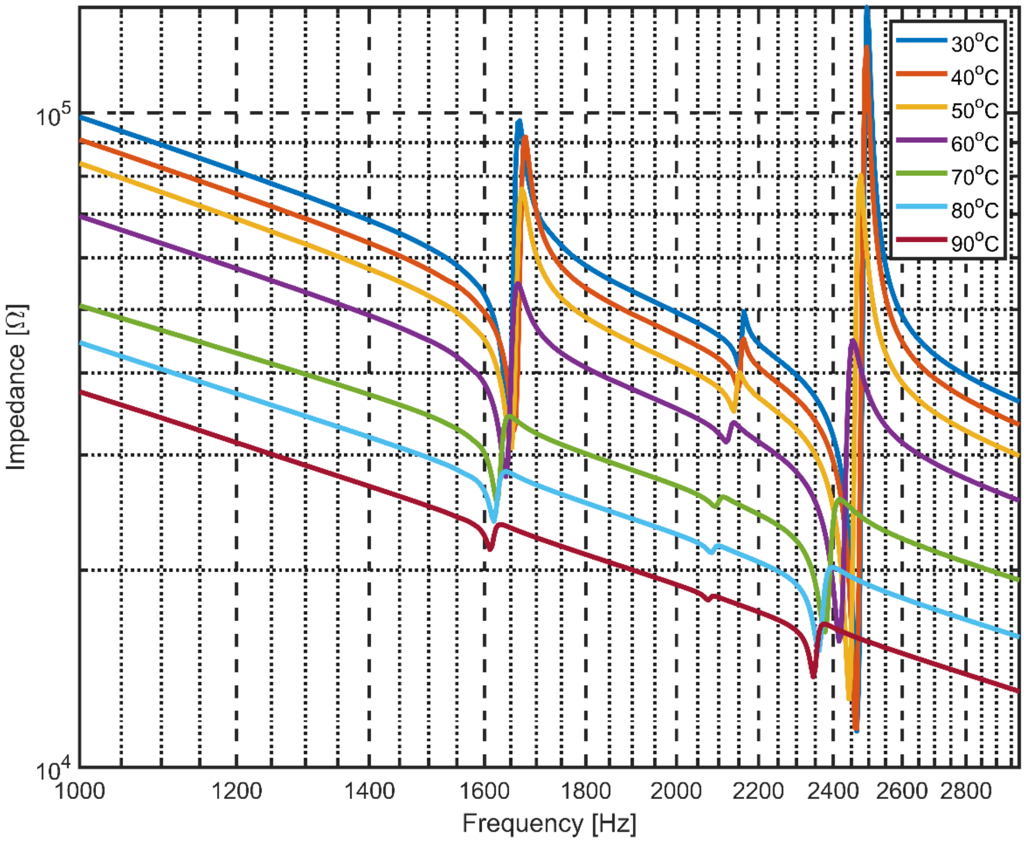

Fig. 7: Measured impedance for energy harvesting device as a function of frequency for a 1 V drive at various temperatures

The impedance analysis confirms that the frequency of each mode reduces as the temperature increases (Figure 7). The measured reduction in frequency for the first mode is 42 Hz, a little lower than the predicted value of 52 Hz. The second and third modes reduced by 78 Hz and 122 Hz, respectively, which is also a little lower than predicted (i.e. 89 Hz and 135 Hz). Nonetheless, the impact of temperature is captured by the model with fair accuracy.

Conclusions and Future Work

A topologically optimised energy harvesting device reported in [2], designated as the "topology-3" harvester, has been EDM wire cut and clamped using a new mounting system. The "topology-3" harvester was designed to harvester from multiple prominent gear meshing frequencies of a Bell 206-B Kiowa Helicopter main rotor transmission, with the first mode at 1900 Hz, second mode 2250 Hz, and third mode 2500 Hz. Earlier studies [2 and 9] found that the dynamic response of the device was extremely sensitive to the manufacturing process and clamping arrangement. The updated manufacturing process and mounting system was found to significantly improve the performance of the devices in a laboratory environment, displaying consistent behaviour to the multi-physics model within experimental uncertainty. The new "topology-3" harvesters were subjected to elevated temperatures, in the range of 20°C to 90°C, representative of a helicopter gearbox environment. The effect of the elevated temperatures on the dynamic performance of the harvesting devices was quantified both in a laboratory environment and using the multi-physics model. Good agreement between the experimental and numerical results was observed, with all modes of interest reducing in frequency. The first mode was predicted to reduce by 52 Hz and a reduction of 42 Hz was measured in the experiment. The second and third mode were predicted to reduce by 89 Hz and 135 Hz, respectively, close to the measured reductions of 78 Hz and 122 Hz, respectively. Future work will be to place the devices on the helicopter gearbox to determine their performance under operation conditions as well as mitigate the performance degradation as a result of temperature.

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