CHARACTERIZATION AND IN SITU TEST OF VIBRATION TRANSDUCERS FOR ENERGY-HARVESTING IN AUTOMOBILE APPLICATIONS

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Abstract: In automobile applications there are a growing number of processes which needs to be controlled and monitored using a diversity of sensors. This paper focuses the conversion of car engine vibration into electrical energy as a potential power supply for remote sensors systems. The “order–related” phenomenon of engine vibration is used to define most energetic vibration frequencies at a four–cylinder in–line engine. Subsequently three electromagnetic resonant vibration transducers have been assembled according to voltage optimization procedure. Power measurements of in situ tests for different operational profiles of the engine are used to confirm the outcome of the “order–related” preliminary frequency selection.

Key words: Vibration energy harvesting, Order domain analyses, Resonant vibration transducer, car engine

1. INTRODUCTION

Over the past decades there has been a steady increase of sensor applications in automobiles. Beyond vital functions and the control of the combustion process the increase of comfort is a major task. Especially for the last–mentioned the number of applications would increase even more in automobile industry if wired solutions could be replaced by wireless sensor nodes. However one challenge is the realization of the power supply for such remote sensor nodes which needs to be reliable, maintenance free and economic, at the same time. Beyond primary batteries and near field–coupling energy harvesting is a promising approach to power such remote sensor applications.

This paper describes the conversion of engine vibration into electrical energy using electromagnetic resonant vibration transducers. The characteristics associated with a four–cylinder in–line engine will be discussed first. Based on order domain analysis the choice of resonant frequency is carried out after that. Lastly results of in situ tests performed with prototype electromagnetic resonant vibration transducers will be discussed.

2. ENGINE VIBRATION AND ORDER DOMAIN ANALYSES

One typical characteristic of resonant vibration conversion is the limitation to narrow band operation. Therefore it is important to know the expected excitation conditions for the design process. The ideal conception is to have a well defined vibration source with a constant frequency as an excitation. However as the intended operational environment for the resonant vibration transducers described in this paper is a car engine the typical vibration characteristic will change over time in an unforeseeable manner. Nevertheless it is possible to define energetic vibration frequencies using the order domain analysis which correlates the vibration frequency with the revolution speed. A typical crankshaft drive of a car engine is given in Fig. 1. The rotation of the crankshaft produces oscillating and rotating inertial forces. The oscillating forces can

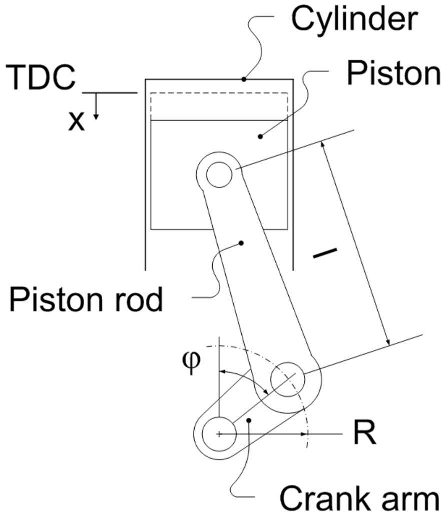


Fig. 1: Crankshaft drive of a car engine

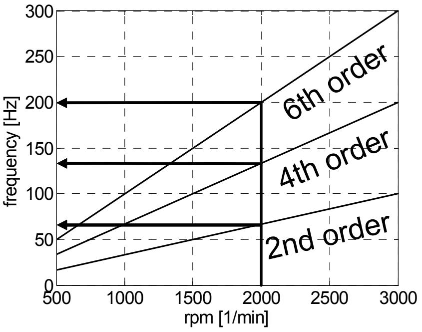


Fig. 2: Campbell diagram of a four cylinder in–line engine (frequencies marked for rpm=2000 min^{-1})

be derived using the acceleration of the piston:

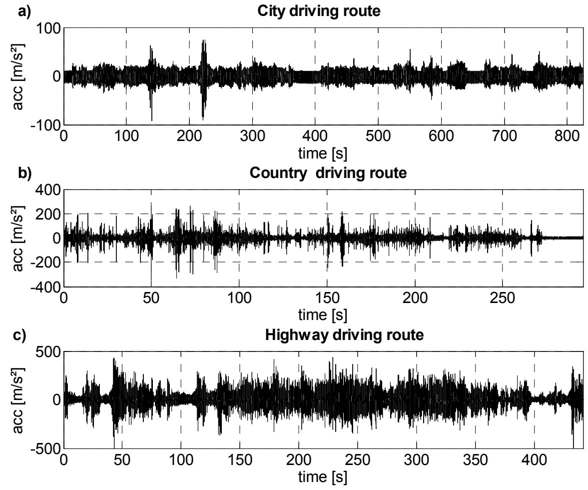
$$\ddot{x} = R\cdot(2\pi N)^2\cdot(\cos\varphi + \lambda\cdot\cos 2\varphi). \qquad (1)$$

Therein indicates N the number of revolutions per second and $\lambda=R/l$ the ratio of the crank arm length to the piston rod length. In contrast to the piston and the piston rod the crank arm is normally balanced and does not produce oscillating forces. The oscillating force can be defined as:

$$m_{osc} = m_{piston} + m_{pistonrod},$$
$$F = m_{osc}\cdot\ddot{x} = \underbrace{m_{osc}R\omega^2\cos\varphi}_{\text{first oder}} + \underbrace{m_{osc}R\omega^2\lambda\cos 2\varphi}_{\text{second order}}, \qquad (2)$$

where $\omega=2\pi N$ is the angular speed. The engine we want to consider in the following is a four–cylinder in–line diesel engine where the four pistons have a pairwise 180° phase shift (Cylinder 1 → 0°, Cylinder 2 → 180°, Cylinder 3 → 360°, Cylinder 4 → 540°). In this case the first order terms will be compensated ($\cos\varphi = 1$; $\cos\varphi = -1$, respectively) in spite of the second order terms which will be add! In general the lowest measurable engine order is obtained by dividing the number of cylinders by two. The revolution dependent frequency of n^{th} order can be calculated with:

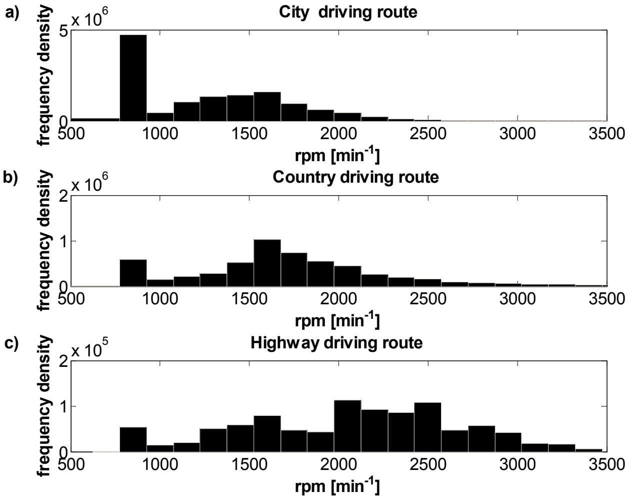
$$f = \frac{rpm}{60}\cdot n, \qquad (3)$$


a) City driving route

b) Country driving route

c) Highway driving route

Fig. 3: Example acceleration profile for a) city–, b) country– and c) highway driving route


a) City driving route

b) Country driving route

c) Highway driving route

Fig. 4: Revolution per minute histogram for a) city–, b) country– and c) highway driving route

Table 1: Suggested resonance frequencies for the vibration transducer based on order domain analyses

Driving route	**resonance frequencies [Hz]**		
	2$^{\text{nd}}$ order	**4$^{\text{th}}$ order**	**6$^{\text{th}}$ order**
City	53	106	160
Country	53	106	160
Highway	66-83	133-166	200-250

where *rpm* indicates the revolutions per minute. A plot of the integer natural harmonics as a function of the number of revolutions is called a "Campbell diagram" (Fig. 2). In application the *rpm* correlated frequency spectrum of acceleration measurements are often used to construct such a Campbell diagram. Representative acceleration profiles of a city–, country– and highway driving route measured at a component in the engine compartment is shown in Fig 3. A histogram from the overall collected *rpm* data is given in Fig. 4. The idle speed is clearly visible in the diagrams (850 min^{-1}). Moreover the most frequently *rpm* for City– and Country driving route is 1600 min^{-1} and 2000–2500 min^{-1} for the highway driving route respectively. With these results and (2) suitable resonance frequencies of the vibration transducer can be defined. The results are given in Tab. 1. In the frequency

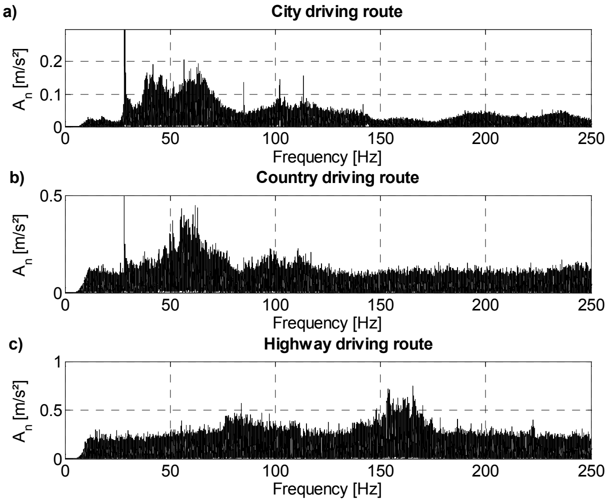


Fig. 5: Frequency content of the example acceleration profiles

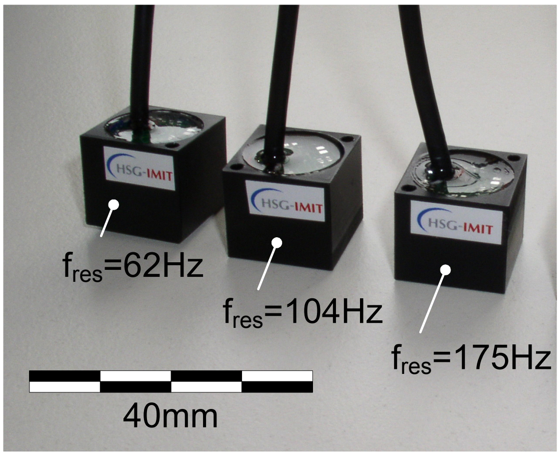


Fig. 6: Prototype vibration transducers assembled for the in situ characterization

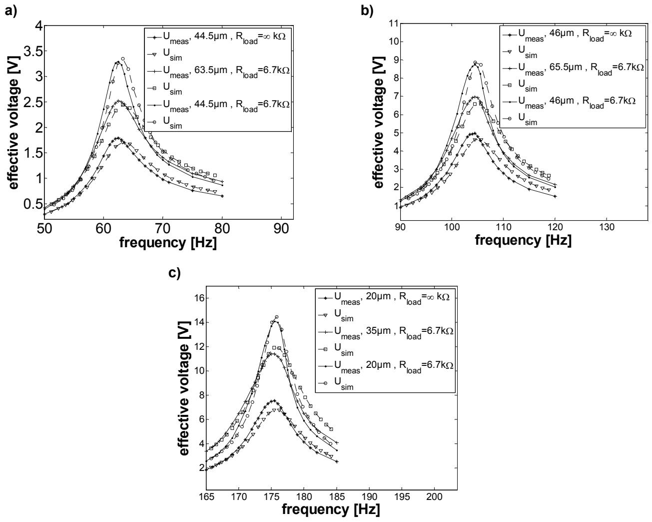


Fig. 7: Results of frequency response simulation compared to measurement on a lab shaker. a) transducer for 2nd order– b) transducer for 4th order– and c) transducer for 6th order conversion

content of the acceleration profiles (Fig. 5) these resonance frequencies are within a plateau of high acceleration amplitudes. For city– and country driving route the 2nd order and for the highway driving route the 4th order frequencies reaches the highest amplitudes. However the proportionalities of the generated output power for excitation at resonance frequency is given by [1]:

$$P=\frac{m\xi_e\frac{1}{\omega_n}\left(\frac{\omega}{\omega_n}\right)^2}{\left(\left(2\xi_t\frac{\omega}{\omega_n}\right)^2+\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2\right)}\ddot{Y}_0^2\xrightarrow{\omega=\omega_n}P\sim\frac{\ddot{Y}_0^2}{\omega_n},\quad(4)$$

where m indicates the oscillating mass, ξ_e the viscous damping due to electromagnetic coupling, ξ_t the sum of viscous damping due to electromagnetic coupling and mechanical loss, Y_0 the displacement amplitude of vibration, ω the angular frequency of vibration and ω_n the resonance angular frequency of the system. From this it is apparent that also for the highway driving route the generated power for 2nd order conversion will be as high as for 4th order conversion. Taking all these results into account the highest output power levels are expected for the frequency band correlate to the 2nd engine order.

3. CHARACTERISATION AND IN SITU PERFORMANCE OF PROTOTYPE VIBRATION TRANSDUCERS

For practical tests three prototype vibration transducers have been assembled according to the voltage optimization procedure described in [2] (Fig. 6). The resonance frequencies are chosen to convert the 2nd, 4th and 6th engine order. A comparison of simulated and measured frequency response curves for different excitation amplitudes (open circuit operation and with resistive load) are shown in Fig. 7. With the internal resistance of the coil the optimal load resistance has been determined [3] and experimentally verified (R_{coil}=2 kΩ, R_{load}=6.7 kΩ). The voltage levels for the lab shaker measurements are rather high. This is because the excitation amplitudes for the lab shaker measurements are comparatively high as well. Nevertheless in the application the voltage is a critical point since levels much lower than 1 V can not be rectified effectively [4]. A typical output voltage of the in situ test is given in Fig. 8. Even though the maximum output voltage and power levels are rather high (6 V and 5.4 mW) the base level of the voltage is about 1 V which is the lower limit for the effective processing with normal semiconductor devices. At this

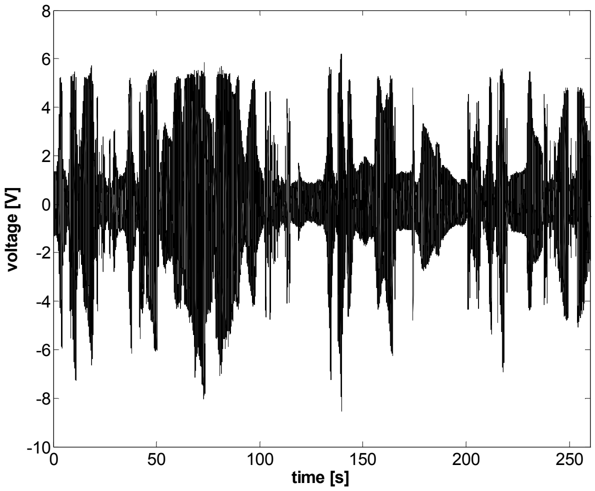


Fig. 8: Example output voltage for country driving route (62 Hz, 2^{nd} order conversion)

point it is obvious to address the voltage as the objective function for optimization. A power optimized transducer would of course result in higher maximum output power levels but also in a voltage base level far below 1 V. Therefore the even more important mean value of the available output power (after rectification) would be much lower (increasing time periods with too small voltage levels). As expected from the order domain analyses together with the FFT calculations the highest mean values of voltage and power levels have been obtained for the conversion of the 2^{nd} engine order (f_{res}=62 Hz). With a transducer volume of 2.9 cm³ (without electronics) mean values of around 290 µW have been obtained for city driving route, 580 µW for country driving route and 280 µW for highway driving route.

CONCLUSIONS

The conversion of car engine vibration into electrical energy using resonant vibration transducers have been presented in this paper. First the order domain analysis of a car engine has been discussed. The results from this theoretical analysis together with acceleration measurements are than used to define resonance frequencies where the most output power is expected. Based on these resonance frequencies three prototype vibration transducers have been assembled according to a voltage optimization procedure. In situ test on a four–cylinder in–line engine were performed and discussed for different driving routes (city–, country– and highway driving route). Independent of the driving route it was shown that the most power is generated for the conversion of the 2^{nd} engine order which corresponds to a resonance frequency of around 60 Hz. However this frequency depends on the frequency density of the revolution speed and the number of cylinders. The maximum output level of the prototype transducer was 6 V and 5.4 mW. The highest mean value of the output power was obtained for country driving route (580 µW). This power level is enough to perform a lot of sensor applications. Nevertheless, it has to be noted that this values are obtained for frequency adaptation to the given car engine and optimal alignment of the sensible axis of the transducer (direction of vibration). In application this could be rather difficult to be guaranteed.

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