UNIVERSITY OF Southampton
Institute of Sound and Vibration Research

ISVR Technical Memorandum

Vibration Power Harvesting from Head Motion

R. Saba, S.J. Elliott and O. Baumann

ISVR Technical Memorandum No 998

November 2012

SCIENTIFIC PUBLICATIONS BY THE ISVR

Technical Reports are published to promote timely dissemination of research results by ISVR personnel. This medium permits more detailed presentation than is usually acceptable for scientific journals. Responsibility for both the content and any opinions expressed rests entirely with the author(s).

Technical Memoranda are produced to enable the early or preliminary release of information by ISVR personnel where such release is deemed to the appropriate. Information contained in these memoranda may be incomplete, or form part of a continuing programme; this should be borne in mind when using or quoting from these documents.

Contract Reports are produced to record the results of scientific work carried out for sponsors, under contract. The ISVR treats these reports as confidential to sponsors and does not make them available for general circulation. Individual sponsors may, however, authorize subsequent release of the material.

Vibration Power Harvesting from Head Motion

Rami Saba, Steve J. Elliott and Oliver Baumann

ISVR Technical Memorandum No. 998

November 2012

UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

INSTITUTE OF SOUND AND VIBRATION RESEARCH

SIGNAL PROCESSING AND CONTROL GROUP

Vibration Power Harvesting from Head Motion

by

Rami Saba, Steve J. Elliott and Oliver Baumann

ISVR Technical Memorandum TM998

November 2012

Authorized for issue by

Professor Paul R White

Abstract

Electrical power is required for a number of measurement and medical devices that are implanted in the head. A feasibility study has been undertaken to estimate the maximum electrical power that could be harvested from the different axes of the linear and angular movements of a person's head when walking. A tuned inertial device was assumed in each case, whose throw was limited by its size, and it was found that most power was generally available by harvesting from vertical head motion. The power available from the fundamental component by tuning the device to the walking frequency is predicted to be about 60 μW for a 1 cm^3 device. Although more power is shown to be available from higher harmonics, this requires a lightly damped device that would respond significantly at only one walking speed. The higher harmonics also contribute to the power harvested by a heavily damped device, however, which is additionally able to respond to a range of walking speeds. The predicted power output for a 1 cm^3 device is then about 80 μW.

Keywords: Power Harvesting, Cochlear Implant, Resonant vibration, Electromagnetic

Acknowledgements

The work of Rami Saba was funded by the Rayleigh Scholarship from the Institute of Sound and Vibration Research at the University of Southampton .

Contents

List of Figures

List of Tables

1 Introduction

A number of implanted measurement and medical devices require electrical power. While this power could be supplied by batteries, which could be replaced or externally recharged, it is of interest to consider the power that could be generated from the motion of the body (Thad et al., 2004). Of particular interest here are medical devices, such as the cochlear implant, mounted within the head and the possibility of powering them from normal head motion, while walking, for example. Clearly a person will only be moving about, and thus generating power from head motion, for a fraction of the time and so the average power available will be significantly less than the peak. Other head implanted measurement and medical devices include cranial pressure monitors (Ginggen et al., 2008), brain stimulators (Mogilner et al., 2001) penetrating auditory nerve array (Middlebrooks and Snyder, 2007) and are anticipated to have requirements ranging from a few µW to several mW. There is also significant interest in cochlear implants or penetrating nerve arrays that have no external parts, and although a large number of technological issues need to be addressed with such devices, their powering is one particular concern.

This report is a development of earlier work by Saba (2008), and discusses the dynamics of an inertial device for harvesting power, for both linear and angular motion and derives simple rules for the way in which this power scales with the size of the device. The proportion of this harvested power that can be converted into electrical form is then analysed, which is shown to depend on a non-dimensional coupling factor, the magnitude of which is also shown to scale with device size. The problem of using a small device to harvest power from head movement, where the excitation amplitude is much greater than the device size, is rather different from most conventional power harvesting applications (Glynne-Jones and White, 2001), where the excitation amplitude is much smaller than the device size. It is thus important to return to the fundamental equations that govern such a device to estimate the available power.

Previous measurements of head motion in all six linear and angular directions while walking are then used to estimate the maximum electrical power that could be generated by a harvesting device of 1 cm^3, assuming power is harvested by tuning the device to the fundamental walking frequency. The scaling law for power harvesting predicts that the power available is proportional to the vibration amplitude times the excitation frequency cubed. This prompts a study of power harvesting from higher harmonics of motion, which have lower amplitudes but higher frequencies. This requires the acquisition of higher bandwidth measurements of head motion than were previously available.

2 Dynamics of an inertial harvesting device

Figure 1 illustrates the main components of an idealised inertial device for harvesting power from linear motion along its axis. The details of the transduction mechanism are set to one side for the time being and it is assumed that half the power dissipated in the viscous damper, c, is available for harvesting. This factor of two will be justified, using the example of an electromagnetic device, in the following section.

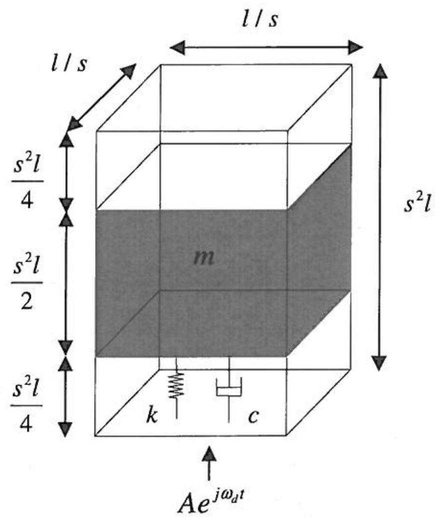

Figure 1: Idealised sketch of an inertial device for harvesting power from the imposed sinusoidal motion having displacement of and angular frequency ω_d .

The device is assumed to have dimensions $l/s \times l/s \times s^2 l$, where l is a characteristic length and s is a dimensionless shape factor, so that the volume is always l^3, and s would equal unity if the device were cubic, for example. It is driven along its axis by sinusoidal motion of peak displacement A and angular frequency ω_d . The vertical displacement is thus equal to the real part of $Ae^{j\omega_d t}$, which is assumed to produce a displacement of the inertial mass equal to the real part of $Be^{j\omega_d t}$. The complex relative displacement between the base and the inertial mass is then equal to

$$A - B = \frac{-\omega_d^2 m A}{j\omega_d c + k - \omega_d^2 m} \tag{1}$$

The maximum power that can be harvested from a practical device is half the power dissipated in the damper, c, as discussed in section 3, and this is equal to

$$W = \frac{1}{4} c\, \omega_d^2 \left| A - B \right|^2 \tag{2}$$

which is then equal to the result by Williams and Yates (1996),

$$W = \frac{cm^2\,\omega_d^6\,A^2}{4\left|j\omega c + k - \omega_d^2 m\right|^2}. \tag{3}$$

Assuming that the system is operating at resonance, so that $k = \omega_d^2 m$, then the power becomes

$$W = \frac{m^2\omega_d^4 A^2}{4c} \tag{4}$$

This suggests the apparently paradoxical result that an infinite power could be harvested if the damper were to become negligible (Stephen, 2006). Physically the mechanical load impedance presented by the device would become infinite under these conditions, but of more importance practically, the throw of the inertial mass would also become infinite.

We thus assume that the damping in the device is adjusted so that the throw of the internal mass is limited to the maximum allowance within the enclosure, equal to $\pm\Delta$, so that using equation (1) with k equal to $\omega_d^2 m$,

$$c = \frac{m\omega_d A}{\Delta} \tag{5}$$

Note that the damping must then depend on the excitation amplitude as well as the maximum throw. Substituting this value of c into equation (4) gives the maximum power available for harvesting as (Stephen, 2006, Yeatman, 2008, Saba et al., 2008),

$$W = m\,\omega_d^3\,A\Delta / 4 \tag{6}$$

We now assume that for a power harvesting device having the linear dimensions as above, the inertial mass has dimensions of $l/s \times l/s \times s^2 l/2$ and is of density ρ, so that m is equal to $\rho\, l^3/2$. We also assume that the maximum throw, Δ, is equal to $s^2 l/4$, as indicated in Figure 1. Under these circumstances the power available for harvesting, equation (6), is equal to

$$W = s^2 \rho A \omega_d^3 l^4 / 32 \tag{7}$$

Clearly the available power is larger as the device becomes longer and thinner, so that s is greater than one. For practical reasons, however, we assume that s^2 can be no larger than 2, so that the maximum power that can be harvested will be

$$W = \rho A \omega_d^3 l^4 / 16, \quad (8)$$

which is in a convenient form for scaling studies. In the calculations below, ρ is assumed to be equal to 7860 kg.m-3, i.e. that of steel, since the inertial mass is often also required to supply the magnetic field in electromagnetic devices. One potential problem with using vertically-orientated inertial devices tuned to walking speeds, and so having low natural frequencies, is that if the spring is linear, it has a large deflection due to the influence of gravity on the mass. This can be avoided by using a nonlinear spring, with a high static stiffness, to support the weight of the mass, and a low dynamic stiffness, to achieve the required natural frequency. A number of nonlinear mechanisms designed to achieve this for vibration isolation applications, where a similar need arises, have recently been reviewed by Ibrahim (2008).

A very similar analysis can be performed for angular excitation of a tuned rotational system (Yeatman, 2008, Saba et al., 2008). In this case, the maximum power available for harvesting, assumed again to be half the power dissipated, is not limited by the maximum angular displacement, which could be very large in a well-designed device, but is limited by the minimum practical damping ratio of the device, ζ, so that

$$W = \frac{I \omega_d^3 \theta^2}{8\zeta}, \quad (9)$$

where I is the moment of inertia of the mass and θ is the imposed angular displacement. In practice one would like the damping to be almost entirely provided by the electrical power harvesting mechanism, which must thus be set to be significantly higher than the inherent mechanical damping in the device. Assuming that it would be difficult to get the mechanical damping ratio below 1%, a reasonable value for the total damping ratio, ζ, may be 10%. Also, assuming that the inertial mass is a cylinder of length $s^2 l$ and radius $l / 2s$, where s is again a dimensionless shape factor, its moment of inertia, I, is equal to $\pi \rho l^5 / 32 s^2$. In this case the power available is increased as the device becomes thinner and flatter, i.e., s is smaller than one. Assuming, however, that for practical reasons s^2 can be no smaller than ½, the maximum power available for harvesting from an angular displacement of θ is thus approximately

$$W = \rho \theta^2 \omega_d^3 l^5 / 4. \quad (10)$$

Yeatman (2008) has also estimated the power available from a non-resonant rotational device, such as those used in self-powering watches and shown it to be similar to equation (9) with ζ set to 1, so that the resonant device is more efficient, although more highly tuned. This author also shows that one potential method of increasing the power harvested from angular motion is to use a gyroscopic device, although this would then have to have a mechanism to maintain the speed of the gyroscope.

The dependence of the maximum power available for harvesting on l^4 in equation (8) and l^5 in equation (10), suggests that it would be far less efficient to implement multiple micro-miniaturised devices than a single device that is as large as possible. These equations are used in the following section to estimate the power that could be potentially harvested from the various axes of motion of the head.

3 Transduction efficiency

In order to provide an estimate of the proportion of total mechanical power supplied to the inertial harvesting device that can be converted into electrical energy, we consider a two-port representation of the electromagnetic inertial device shown in Figure 2. The equations linking the force applied to the device, f, its velocity, u, and the voltage generated by the coil, v, and current flowing, i, can, in general, be written as (Hunt, 1954)

$$f = Z_M u + T_1 i, \tag{11}$$

$$v = T_2 u + Z_E i, \tag{12}$$

where Z_M is the mechanical impedance of the device when the coil is open circuit, which in this case is equal to

$$Z_M = \frac{j\omega m(j\omega c + k)}{j\omega c + k - \omega^2 m} \tag{13}$$

where m, k and c are the mass, stiffness and damping of the inertial mass on its suspension.

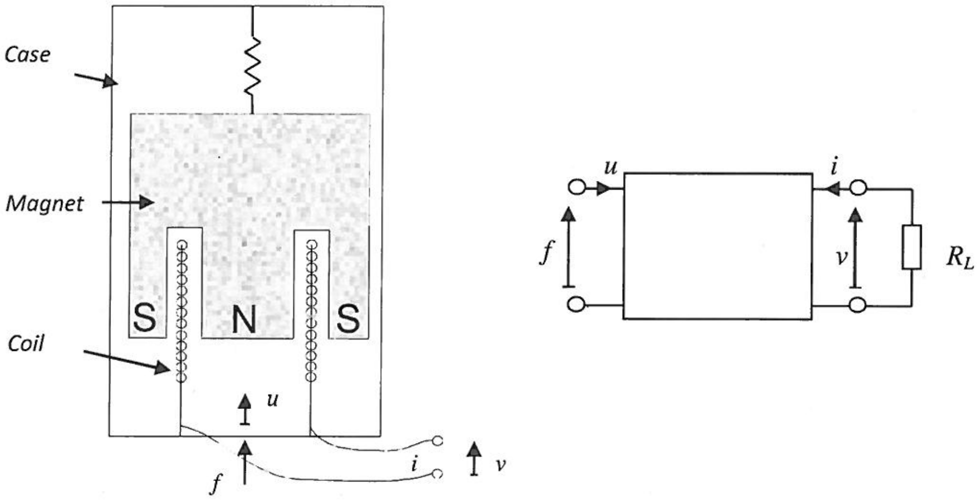

Figure 2: Sketch of an idealised electromagnetic harvesting device, in which the magnet also acts as the inertial mass, *m*, which is suspended by a stiffness k and a viscous damper c, and the coil is attached to the case. The equivalent two-port network is also shown, where the coil is attached to a resistance R_L.

T_1 is a transduction coefficient equal to

$$T_1 = \frac{BLm\omega^2}{j\omega c + k - \omega^2 m}, \tag{14}$$

where BL is the product of the magnet's flux density and the length of wire in the coil. Since the device is anti-reciprocal (Hunt, 1954), then the other transduction coefficient, T_2, is equal to $-T_1$. Z_E is the electrical impedance when the mechanical part is blocked, which is assumed to be entirely resistive and denoted R.

If the electrical terminals of the device are connected to a load resistor, R_L, the dissipation within which is equal to the electrical power harvested, then the power harvested is equal to,

$$W_H = \frac{1}{2} R_L \, |i|^2 \tag{15}$$

But if v is equal to $-R_L i$ in equation (12) then

$$i = \frac{-T_2 u}{R + R_L} \tag{16}$$

so that

$$W_H = \frac{R_L |T_2|^2}{2(R+R_L)^2} |u|^2 \tag{17}$$

The mechanical impedance of the device when connected to the load resistor can also be shown to be equal to

$$Z_M(total) = Z_M - \frac{T_1 T_2}{R+R_L}, \tag{18}$$

and so the total mechanical power supplied to the harvesting device is

$$W_S = \frac{1}{2}\mathrm{Re}\left[Z_M - \frac{T_1 T_2}{R+R_L} \right] |u|^2, \tag{19}$$

where Re denotes the real part of the quantity in brackets. The ratio of the harvested power, W_H, to the power supplied, W_S, can be defined to be the efficiency of the device, which, in general, is equal to

$$e = \frac{R_L |T_2|^2}{(R+R_L)^2 \mathrm{Re}[Z_M - T_1 T_2 / (R+R_L)]} \tag{20}$$

If the inertial device is driven at ω_d and is assumed to be operating at resonance, so that $k = \omega_d^2 m$, then $\mathrm{Re}[Z_M]$ is equal to km/c, and $-T_1 T_2 = |T_2|^2 = (BL)^2 km/c^2$. Differentiating the resulting expression for e with respect to R_L and setting this to zero shows that the maximum power is harvested when R_L is equal to R. Under these conditions, the power harvesting efficiency can be written as

$$e = \frac{F}{4+2F} \tag{21}$$

where F is a non-dimensional transduction coupling factor, as derived in a different context (Nakano et al., 2007), which is given by

$$F = \frac{(BL)^2}{Rc} \tag{22}$$

The coupling factor will be large if the magnet is strong and the length of wire in the coil is large, so $(BL)^2$ is large, and if the electrical resistance of the coil and intrinsic mechanical damping is small. When F is much greater than unity then the efficiency, e, in equation (21) tends to ½, since negligible power is dissipated in the intrinsic mechanical damping, c, so all the power is dissipated by the circulation of the current, and half of this is harvested in the matched load R_L. It is this limiting condition that is assumed above.

It is also interesting, however, to estimate how this transduction coupling factor, F, scales with size, and thus see how difficult it would be to achieve this limiting condition as the device dimensions are made smaller. Assuming that B is independent of size, but that L is proportional to length scale l, R, which equals the resistivity times coil length over wire area, is proportional to l^{-1} and the intrinsic mechanical damping is proportional to l (J.Piers, 2001), then F is proportional to l^2 and it becomes progressively harder to maintain its value well above unity as the device is made smaller.

4 Estimates of power available from various axes of head motion

Both the linear head acceleration in all three axes and that in the three axes of angular head acceleration were measured in 12 subjects while walking by Woodman and Griffin (1996). Typical waveforms for the acceleration in all directions are shown in Figure 3.

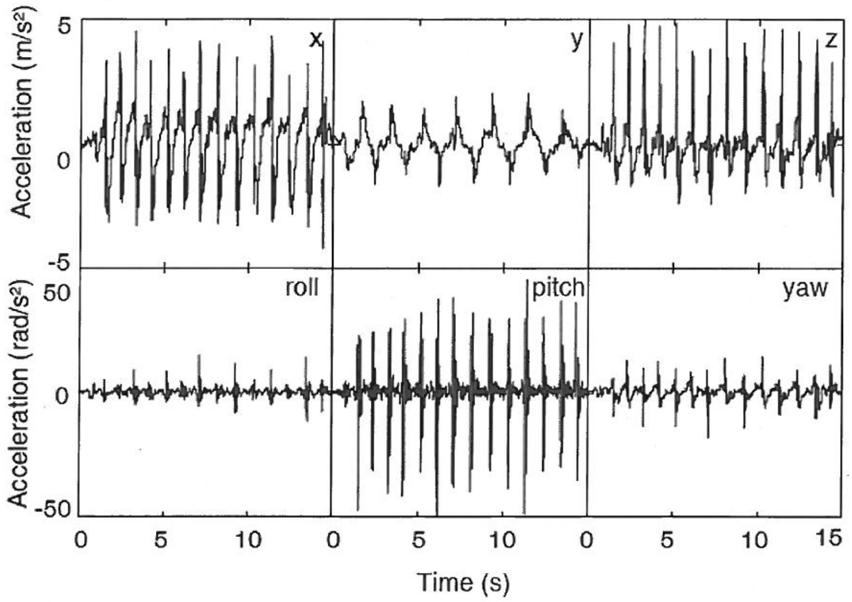

Figure 3: Acceleration time histories at the head in six axes for a single subject walking at 1 steps/s taken, with permission, from P.D. Woodman, M.J. Griffin, Six axes of head acceleration during ambulation, Proc. Inter-noise 96, pp.1719-1724, 1996.

The amplitude in the z (vertical) direction is higher than that in the y (side to side) or x (forward and aft) directions. From the power spectra of these waveforms, the fundamental excitation frequency and the amplitude of motion at this frequency were estimated for different walking speeds, as shown for z - axis motion in Table 1. Equation (8) from section 2 was then used to estimate the maximum power available for energy harvesting using a 1 cm^3 device at each walking speed, which is also listed in Table 1. At a normal walking speed of about 1.5 steps per second, the maximum power available from a 1 cm^3 device was calculated to be about 60 μW for the z - axis (vertical) motion. This is about twice that available from the x-axis motion at this walking speed, for example.

Walking speed (steps/second)	1	1.25	1.5	1.75	2	2.25
Fundamental frequency (Hz)	1	1.25	1.5	1.75	2	2.25
Linear amplitude (mm)	14	10	16	10	13	13
Power available from linear motion for 1 cm^3 device (μW)	17	40	64	94	125	125
Angular amplitude (radians)	0.018	0.02	0.011	0.01	0.009	0.007
Power available from angular motion for 1 cm^3 device with 10% damping (μW)	0.016	0.03	0.02	0.02	0.04	0.03

Table 1: Fundamental frequency (Hz), maximum linear amplitude (mm), maximum angular amplitude together with estimated power available for harvesting from the fundamental component of the translational motion in the vertical axis and the angular motion in the pitch direction, for various walking speeds, using the data from Woodman and Griffin (1996).

The angular acceleration of the head motion in the pitch direction is also significantly greater than that in the roll or yaw directions. The angular displacement calculated from the measured angular accelerations is also listed in Table 1 at each walking speed together with the associated available power calculated using equation (10) from section 2. The power available is significantly less than that potentially available from the vertical motion in Table 1, being about 0.02 μW for a 1 cm^3 device with a damping ratio of 10% at a walking speed of 1.5 steps per second, for example.

5 Power available from higher harmonics

The initial calculations presented in section 4 suggested that the most likely source of power for harvesting was from the vertical motion of the head. Bandwidth limitations in the original measurements (Woodman and Griffin, 1996), however, prevented them from being used to calculate the potential power available from higher harmonics of the fundamental head motion frequency. Equation (7) in Section 2 suggests that the power available is proportional to $A\omega_d^3$ for a device of a given size, which is equal to ω_d times the acceleration. Thus, even if the acceleration is slightly lower at the higher harmonics, the linear dependence on frequency may make it more worthwhile to tune the inertial system to this higher frequency.

A series of measurements was thus carried out by Saba (2008) with an MIE triaxial accelerometer mounted on a headband, and attached to a portable data logger (Online, 2004). The apparatus and the experiments on a treadmill are illustrated in Figure 4. Figure 5 shows the power spectra of the vertical acceleration when walking at about 1.6 steps per second on the treadmill. Significant energy is contained in the first five harmonics and the measurements are well above the noise floor at these frequencies. Plotting the acceleration multiplied by frequency, i.e., $A\omega_d^3$, shows that the power available from the third harmonic is about three times that available from the fundamental. The amplitude of the fundamental vertical motion was in reasonable agreement with that measured by Woodman and Griffin (1996) and the predicted power available from the fundamental was comparable to the 60 µW prediction above.

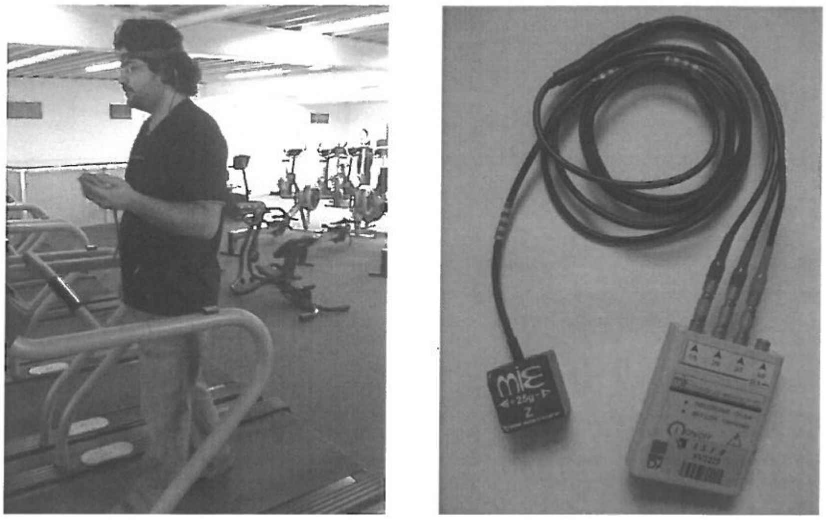

Figure 4: Equipment used to measure head motion and its use on the treadmill.

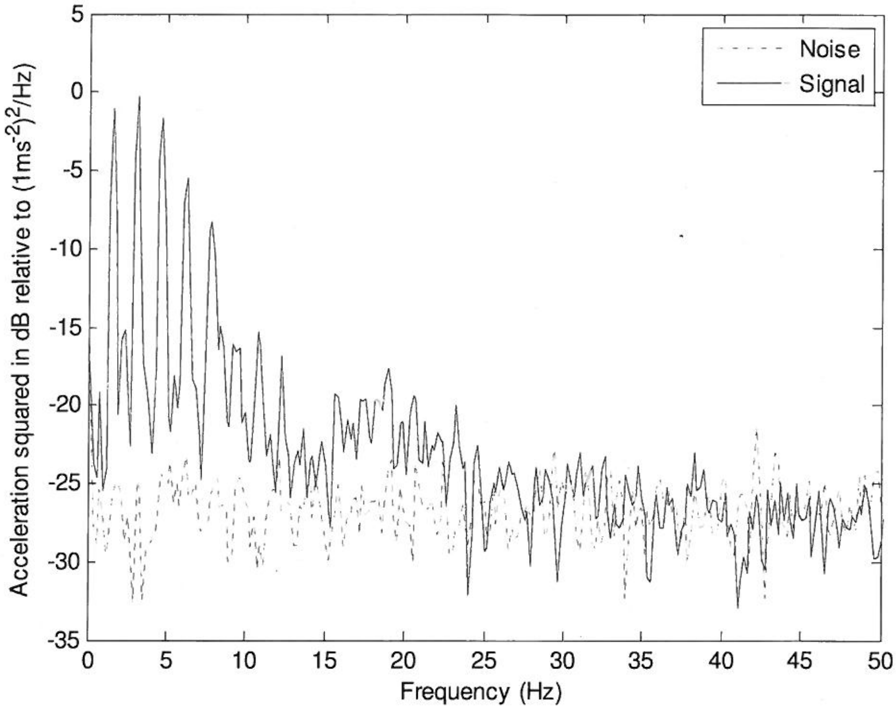

Figure 5: Power spectral density of vertical head acceleration at a walking speed of 1.6 steps per second on the treadmill.

Table 2 shows the frequency at which most power was available for various walking speeds measured by Saba (2008) on the treadmill together with the estimated power available from a 1 cm^3 device. At a walking speed of 1.6 steps per second, the potential power available from the third harmonic is about 130 µW.

Walking speed (steps/second)	1	1.4	1.6	2.1	2.7
Dominant frequency (Hz)	3	4.1	4.8	10.3	18.3
Power available, in µW, from the dominant frequency	35	116	131	206	1044
Power available, in µW, from entire waveform with a single device having a natural frequency of 1.6 Hz and a damping ratio of 2	14	41	80		

Table 2: This shows the frequency at which most power was available for various walking speeds measured by Saba (2008) on the treadmill together with the estimated power available from a 1 cm^3.

6 Harvesting from multiple harmonics

To constrain the motion of the inertial mass so that it does not strike the case when excited at a single frequency, the total damping has to be adjusted according to equation (5). The damping ratio corresponding to this value of damping is equal to

$$\zeta = \frac{A}{2\Delta} \tag{23}$$

which, for a typical fundamental amplitude of vibration (16 mm in Table 1) and size of device (7 mm x 7 mm x 20 mm, so that Δ is equal to 5 mm), is greater than unity.

An inertial device tuned to harvest power from the fundamental component of head motion would thus be very well damped and would have a significant response to several of the harmonics due to a walking motion. This is in sharp contrast to devices designed to harvest power from the high frequency motion of machines, where the driving displacement is very small compared to the device size and so the aim is to design a resonant device with as little damping as possible (Glynne-Jones and White, 2001), and the tuning becomes a significant problem. In fact, it is not clear how such a heavily damped device should be tuned since, if it is tuned to the fundamental, as in section 4, then it will also respond to the harmonics and if it is tuned to a harmonic as in section 5, it will also respond to the fundamental.

A numerical study has thus been conducted using the measured waveform of the vertical acceleration signal, in which the natural frequency of the inertial device has been varied, and for each natural frequency, the damping has been adjusted so that the peak throw of the inertial mass, Δ, was 5 mm. The total power harvested is then calculated as half the sum of the power dissipated in the damper due to each harmonic. The results are shown for a walking speed of 1.6 steps/second in Figure 6, together with the damping ratio required to limit the throw to ± 5mm at each assumed value of the natural frequency.

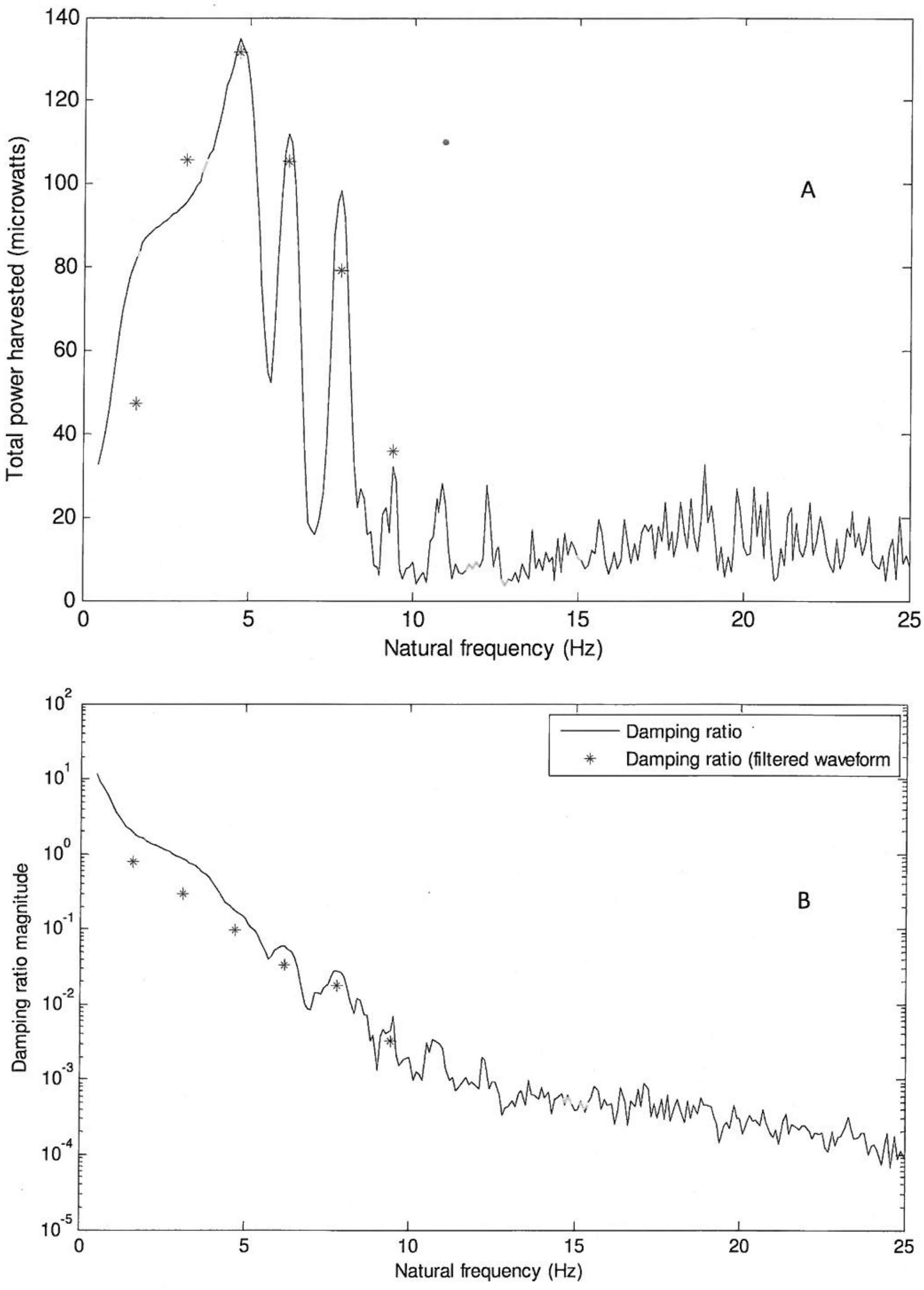

Figure 6: (a) The power harvested from all frequencies against the tuned natural frequency of the inertial device. The stars indicate the calculated power harvested assuming only single frequency excitation at each harmonic. The change in damping ratio with the assumed natural frequency of the harvesting device is also shown in (b), together with that required to limit the motion at each harmonic on its own.

The required damping ratio is high at low natural frequencies, so that the total power harvested when excited by all the harmonics is rather larger than harvested from the fundamental alone, as shown by a star at 1.6 Hz on Figure 6 (a). It should be noted however that the resonant frequency is related to the natural frequency by a factor of $\sqrt{1-\zeta^2}$ and so at high damping ratios the natural frequency at which most of the power is harvested is rather different from the excitation frequency. At the second harmonic, 3.2 Hz, the power available from excitation at this frequency alone is slightly higher than that available from excitation by the whole waveform, since the damping ratio can be allowed to be smaller when only the harmonic is present.

The power harvested is greatest, generating about 130 μW, when the natural frequency is set to the third harmonic, at about 4.8 Hz. The power generated by the individual harmonics is also largest at this frequency, as recorded in Table 2 and is almost the same as that generated when the device is excited by the whole waveform. The damping ratio required to achieve these power levels is about 0.2, however. Such a device would thus be quite sharply tuned, and unable to respond significantly if the walking speed changed by more than about 10%. A more practical solution may thus be to live with the slightly lower power output with the device tuned to the fundamental, for which it must be over-damped, the damping ratio being 2 in Figure 6 (b), in order to benefit from the very broad tuning of this device and its insensitivity to the frequency of excitation. The final row in Table 2, for example, indicates the power available for a single such over-damped device, with a fixed natural frequency of 1.6 Hz and a damping ratio of 2, when driven by the whole waveform at each walking speed. The results are not shown for walking speeds of 2.1 and 2.7 steps/second since the throw then exceeds 5 mm. A device with nonlinear damping could be designed to limit the throw more effectively at various walking speeds, and nonlinear springs have also been suggested as a way of decreasing the sensitivity to excitation frequency.

7 Discussion and Conclusions

This report has considered the maximum power that could be harvested from head motion in order to drive fully-implantable medical devices. The performance of an inertial power harvesting device of a fixed size was analysed, and the scaling laws for the maximum available power from both translational and angular excitation were derived. Previous measurements of head motion in all three translational and three rotational axes while walking (Woodman and Griffin, 1996), were initially used to estimate the power available from the fundamental component of different forms of motion. At a normal walking speed of about 1.5 steps per second, it was found that harvesting from the vertical head motion gave the highest potential power output, which was about 60 μW.

Subsequent measurements of the head motion over a greater bandwidth while walking on a treadmill suggested that somewhat more power could be harvested if the inertial device was tuned to a higher harmonic of the fundamental frequency. Tuning the device to the third harmonic, for example, gave a potential power output of about 130 μW, but resulted in a lightly damped device, which was sensitive to changes in walking speed. A more practical strategy is shown to be using an over-damped device tuned to a lower frequency that is able to respond to all the harmonics in head motion, and which performs well with a wide range of walking speeds.

The maximum power harvested, about 80 μW, is far below that required for current cochlear implants, about 40 mW (Cochlear, 2011) or even the currents required for stimulation, about 1 to 5 mW (Ji-Jon and Sarpeshkar, 2008). This method of powering cochlear implants is thus not practical at the moment, but may be useful in future, fully implanted, designs with much lower power requirements.

References

COCHLEAR. 2011. *RE: Personal communication with Paul Carter, Cochlear Corporation.*

GINGGEN, A., TARDY, Y., CRIVELLI, R., BORK, T. & RENAUD, P. 2008. A telemetric pressure sensor system for biomedical applications. *Ieee Transactions on Biomedical Engineering,* 55, 1374-1381.

GLYNNE-JONES, P. & WHITE, N. M. 2001. Self-powered systems: A review of energy sources. *Sensor Review,* 21, 91-97.

HUNT, F. V. 1954. *Electroacoustics*, Wiley.

IBRAHIM, R. A. 2008. Recent advances in nonlinear passive vibration isolators. *Journal of Sound and Vibration,* 314, 371-452.

J.PIERS. 2001. *Design of micromechanical systems: scale laws, technologies and medical applications.* Katholieke Universiteit Leuven.

JI-JON, S. & SARPESHKAR, R. 2008. A cochlear-implant processor for encoding music and lowering stimulation power. *IEEE Pervasive Computing,* 7, 40-48.

MIDDLEBROOKS, J. C. & SNYDER, R. L. 2007. Auditory prosthesis with a penetrating nerve array. *Jaro-Journal of the Association for Research in Otolaryngology,* 8, 258-279.

MOGILNER, A. Y., BENABID, A.-L. & REZAI, A. R. 2001. Brain stimulation: current applications and future prospects. *Thalamus & Related Systems,* 1, 255-267.

NAKANO, K., ELLIOTT, S. J. & RUSTIGHI, E. 2007. A unified approach to optimal conditions of power harvesting using electromagnetic and piezoelectric transducers. *Smart Materials & Structures,* 16, 948-958.

ONLINE, S. 2004. Data logger manufacturer's website.

SABA, R., ELLIOTT, S. J. & BAUMANN, O. N. 2008. Vibration power harvesting from head motion. *Proceedings of EURODYN 2008, 7th European Conference on Structural Dynamics*, 12pp.

STEPHEN, N. G. 2006. On energy harvesting from ambient vibration. *Journal of Sound and Vibration,* 293, 409-425.

THAD, S., JOSEPH, A. P. & CHRISTIAN, P. 2004. *Human Generated Power for Mobile Electronics*, CRC Press.

WILLIAMS, C. B. & YATES, R. B. Year. Analysis of a micro-electric generator for microsystems. *In:* 8th International Conference on Solid-State Sensors and Actuators (Eurosensors IX), Jun 25-29 1996 Stockholm, Sweden. Elsevier Science Sa Lausanne, 8-11.

WOODMAN, P. D. & GRIFFIN, M. J. Year. Six axes of head acceleration during ambulation. *In:* HILL, F. A. & LAWRENCE, R., eds. 25th International Congress on Noise Control Engineering (Inter-Noise 96) - Noise control: The Next 25 Years, Jul 30-Aug 02 1996 Liverpool, England. Inst Acoustics, 1719-1724.

YEATMAN, E. M. 2008. Energy harvesting from motion using rotating and gyroscopic proof masses. *Proceedings of the Institution of Mechanical Engineers Part C-Journal of Mechanical Engineering Science,* 222, 27-36.