Scientific Research Publishing

Journal of Power and Energy Engineering, 2018, 6, 53-64
http://www.scirp.org/journal/jpee
ISSN Online: 2327-5901
ISSN Print: 2327-588X

Piezoelectric Power Harvesting via Acoustic-Pressure Driven by Low-Speed Wind-Force with Resonating-Tube and Wind-Collector

Seiichi Deguchi[1*], Hiroya Taguchi[1], Hajime Arimura[1], Noriyuki Kobayashi[1], Norifumi Isu[2], Kentaro Takagi[3], Tsuyoshi Inoue[3], Takashi Nozoe[4], Seigo Saito[4], Takahiko Sano[4]

[1]Department of Chemical Process Engineering, Nagoya University, Nagoya, Japan
[2]Analysis & Assessment Center, LIXIL Corporation, Noda, Japan
[3]Department of Mechanical Systems Engineering, Nagoya University, Nagoya, Japan
[4]Fuji Ceramics Corporation, Fujinomiya, Japan
Email: deguchi.seiichi@material.nagoya-u.ac.jp

How to cite this paper: Deguchi, S., Taguchi, H., Arimura, H., Kobayashi, N., Isu, N., Takagi, K., Inoue, T., Nozoe, T., Saito, S. and Sano, T. (2018) Piezoelectric Power Harvesting via Acoustic-Pressure Driven by Low-Speed Wind-Force with Resonating-Tube and Wind-Collector. *Journal of Power and Energy Engineering*, **6**, 53-64.
https://doi.org/10.4236/jpee.2018.611005

Received: July 4, 2018
Accepted: November 24, 2018
Published: November 27, 2018

Abstract

Wind-driven power harvestings attract attentions since their target wind speeds are quite low less than the so-called cut-in wind speed, which is generally recognized as around 3 m/s. The extant power harvestings driven by wind-induced-air-column-resonations (*i.e.* acoustic-pressures) are still lacking simplicity, scale flexibility and solid strategies for practical applications. Therefore, the piezoelectric power harvesters via acoustic-pressures driven by low-speedwind-forces with resonating-tubes and wind-collectors were invented so as to complement all the lacks. The wind-collector as well as the resonating-tube contributed to upraise the power harvesting density. The champion power harvesting density of 19.5 nW/dm^2 could be procured at 2.3 m/s of an artificial wind and the optimal resonating-tube and wind-collector. Power harvesting proofs from the natural wind with low mean speeds down to about 0.6 m/s were successfully obtained. The cut-in wind speed of the prototype piezoelectric power harvester was found to be quite low as about 0.4 m/s, signifying its ubiquity. Finally, a multi-bundle pendant-type piezoelectric power harvester was specifically presented together with professing the solid and multiple strategies for practical applications.

Keywords

Piezoelectric Power Generation, Low Wind Speed, Resonating Tube, Wind Collector, Power Harvesting, Practical Demonstration

1. Introduction

Nowadays, wind-force power generators mean conventional wind-turbine-based wind-force power generators [1] and wind-driven power harvestings with using piezoelectric elements [2] [3]. The conventional wind-force power generators have their respective cut-in wind speeds. Meanwhile, the power harvestings have attracted a lot of attention since their target energy sources are compensating overall range less than the cut-in wind speeds, which are generally recognized as around 3 m/s [1] [4]. Furthermore, the power harvestings are going to widen their applicable fields, because the conventional wind-force power generators are reported to include many drawbacks, such as structural complexity, large volume and weight, high cost of manufacturing and installation, low efficiency and noise [5].

The wind-driven power harvestings have been and are still diversified into various kinds [4] [6] [7] [8]. Among them, flutter power harvestings, where piezoelectric materials having thin beam shapes are directly excited by a wind flow, are actively engaged in investigations [5] [6] [9]. The power harvestings driven by wind-induced-events, which exemplify galloping motions [10] [11], vortex themselves [12] [13] and vibrations [14] [15] [16], have an abundance of variety. Most of the works are aiming to match resonant frequencies of the piezoelectric materials/elements to those of fluttering phenomena/wind-induced-events so as to acquire high energy conversion efficiencies [3] [14] [17]-[22].

Here, acoustic energy itself has been investigated as one of the power harvesting sources because of its ubiquity and environmental friendliness [23] [24] [25] [26]. And, wind instruments, such as organ pipes, saxophones, bassoons and trumpets, are well-known to blare out by means of air-column-resonances. Then they are occasionally called "resonating-air-columns" where only corresponsive standing-acoustic-waves can be formed inside [27] [28]. Consequently, the power harvestings driven by wind-induced-air-column-resonations (*i.e.* acoustic-pressures) have emerged since efficient energy conversions from wind-forces to acoustic-pressures are rightfully realized [29] [30] [31]. However, they are considered to be lucking simplicity, scale flexibility and solid strategies for practical applications. Then, this study has been carried out with taking particular note of such lacks so as to make up for them.

2. Experimental

2.1. Experimental Apparatus

Figure 1 shows a schematic drawing of apiezoelectric power harvesting apparatus via anacoustic-pressure driven by a wind-force at a low-speed together with a "wind-collector". The prototype apparatus was so simple to be composed of a "resonating-tube" and a commercial discotic PZT piezoceramic sounder. The "resonating-tube" was made of acrylic resin, possessing 44 mm in inside diameter. The piezoceramic sounder having 24 mm in diameter with a brazen basement, of which a model number was M442D2 merchandised by NTK CERATEC

Co., Ltd., was glued to the "resonating-tube" bottom. Though the wind instruments as original roots of this study are mainly composed of divaricate tubes with some open ends, the "resonating-tube" has one open end and one closed end shut by the piezoceramic sounder. The "wind-collector" was also made of acrylic resin, possessing a semicircle horizontal cross section and the same inside diameter to the "resonating-tube".

2.2. Experimental Procedures

Figure 2 shows a schematic diagram of the piezoelectric power harvesting experimental setup by an artificial-wind from a commercial electric fan (Air MultiplierAM01 merchandised by Dyson Ltd.). A hot-wire anemometer of the model number testo 435 manufactured by Testo Ltd. was located between the apparatus and the fan. The center of the fan was placed in the same height of the vertical center of the "wind-collector" or at the upper end of the "resonating-tube" in the absence of the "wind-collector".

Firstly, the piezoelectric power harvesting apparatus was assembled by connecting the "resonating-tube", the "wind-collector" and the piezoceramic sounder. Subsequently, the hot-wire anemometer and the piezoceramic sounder were hooked up to an oscilloscope (NR-500, KEYENCE Corporation, Japan) with an uptake-rate of 1.0 MHz, and proper workings of the whole system were confirmed. When some abnormal signal patterns such as no fluctuations, quite high peaks and only positive or negative values were monitored, the whole system was disjointed and reassembled again.

Secondly, the fan was set in a premeditated angle specified as "θ" in Figure 2 with 200 mm interval toward the apparatus. Thirdly, the fan was switched on, and the wind speed monitored by the hot-wire anemometer was regulated at 2.3 m/s, which was less than the generally recognized cut-in wind speed [1] [4].

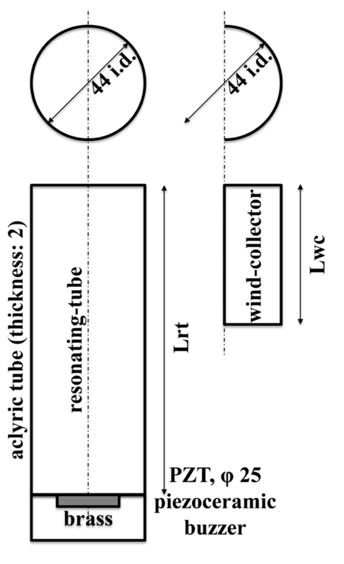

Figure 1. Schematic drawings of piezoelectric power harvesting apparatus and wind collector.

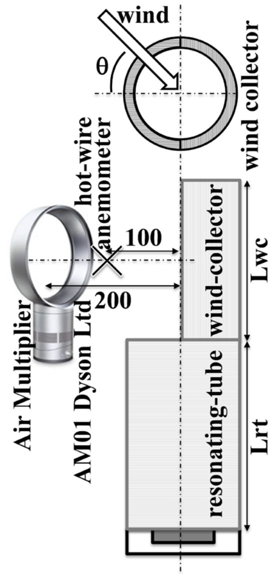

Figure 2. Schematic diagram of experimental setup.

The generated voltages, which were approached steady values as quick as a flash in a great reproducible fashion, were logged for more than 10 min by the oscilloscope. Finally, each root-mean-square voltage calculated from the gigantic raw data was converted into the power harvesting density.

Concerning practical demonstrations, the same experimental setup excluding only the fan was diverted. The apparatus was emplaced outside the laboratory building by a south window on the 5th floor with a concave side of the "wind-collector" facing the outside. The generated voltages and wind velocities were simultaneously logged by the oscilloscope for every 10 min. Then, 10 min mean wind speed was simply calculated, and each root-mean-square voltage was converted into the power harvesting density.

3. Results and Discussion

3.1. Optimal Resonating-Tube Length

As described in the last paragraph in Chapter 1, only the corresponsive standing-acoustic-waves can be formed inside the "resonating-tube" as its name suggests in likewise to the original roots of this study, which are the wind instruments (*i.e.* "resonating-air-columns") [27] [28]. In contrast to "resonating-air-columns" with some open ends where only any fold half-standing-acoustic-wave can exist inside it, the "resonating-tube" has only the one open end and the one closed end, resulting to stable formations of only odd numbers times quarter-standing-acoustic-wave.

Here, the resonant frequency of the adopted piezoceramic sounder, which affects determining influences on the piezoelectric power harvesting efficiency, is roughly addressed from 300 to 900 Hz on its catalog. Supposing that an acoustic velocity is 330 m/s and only the quarter-standing-acoustic-wave is formed inside the "resonating-tube", its appropriate length providing the champion piezoelectric power harvesting density via the acoustic-pressures driven by the wind-forces is calculated to be ranged from 91.7 to 275 mm.

In order to confirm the preceding two paragraphs concerning the appropriate "resonating-tube" length denoted by L_{rt} shown in **Figure 1** and **Figure 2**, experiments have been done with various L_{rt} (see **Figure 3**).

It can be seen from **Figure 3** that the power harvesting density of 69.3 pW/dm^2 without the "resonating-tube" is higher than those with the "resonating-tube" from 40 to 60 mm, resulting that the "resonating-tube" plays a negative role as a windbreaker toward the piezoceramic sounder when its length is inappropriate. Despite such a negative windbreaker role of the "resonating-tube", the higher power harvesting densities reveal with the "resonating-tube" from 80 to 140 mm in this study, comparing with the case without the "resonating-tube".

The champion power harvesting density of 602 pW/dm^2 appears at 90 mm of L_{rt}, which the optimum resonating-tube length for this prototype piezoelectric power harvesting apparatus. This fact tells the following two fruitful outcomes; one is that the positive role of the "resonating-tube" to form only the corresponsive standing-acoustic-waves can defeat the negative windbreaker role when the "resonating-tube" length is appropriate to the piezoceramic sounder, indicating superiority of the prototype piezoelectric power harvesting apparatus, and another is that the resonant frequency of the adopted piezoceramic sounder is determined to around 900 Hz, leading that this utmost simple apparatus is able to offer a different usage as a resonant frequency detector.

3.2. Optimal Wind-Collector Length

Since this piezoelectric power harvester is driven by the odd numbers times quarter-standing-acoustic-wave, of which their amplitudes surely depend on the wind-force, one of the keys for improving the power harvesting density is to increase the wind-force intromitting to the "resonating-tube". Because simplicity is the first priority of this system as stated in the last paragraph in Chapter 1, the quite simple "wind-collector" as shown in **Figure 1** and **Figure 2** with various wind-collector lengths (L_{wc}) has been tested to clarify its effectivity for improving the power harvesting density with the optimal resonating-tube length (L_{rt}) of 90 mm (see **Figure 4**).

It is seen that the "wind-collector" contributes to upraise the power harvesting density. Concretely, the champion power harvesting density of 19.5 nW/dm^2 is procured at 80 mm of L_{wc}, which is the optimal "wind-collector" length for this prototype apparatus. This champion value is about 32 times compared to that without the "wind-collector", and outstrips previous works [2] [4] [6] [7] [25] [32] [33]. Therefore, this system can be concluded to have many advantages such as simplicity, scale flexibility and solid strategies for practical applications, declaring most of these superiorities later on.

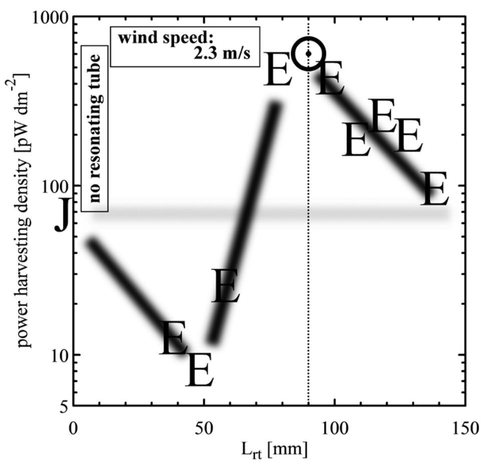

Figure 3. Power harvesting densities with various "resonating-tube" lengths.

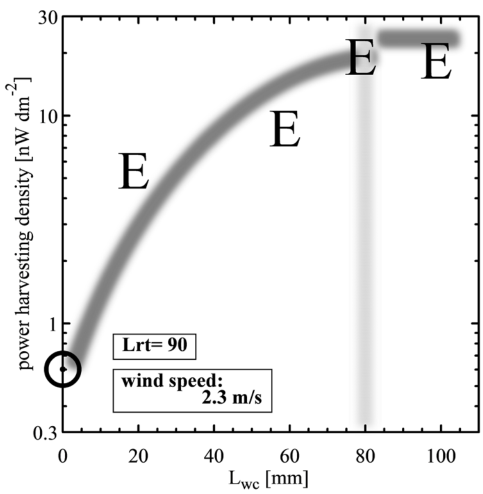

Figure 4. Power harvesting densities with various "winf-collector" lengths.

3.3. Effect of Angle on Power Harvesting Density

A target energy source of this prototype piezoelectric power harvesting apparatus is unsurprisingly the natural wind, especially less than the generally recognized cut-in wind speed of around 3 m/s [1] [4]. Before going to practical demonstrations driven by the natural wind, which is veer and haul, effect of the angle between the apparatus and the fan (*i.e.* "θ" in **Figure 2** and **Figure 5**) on the power harvesting density is examined with the optimal L_{rt} and L_{wc} of 90 and 80 mm, respectively (see **Figure 5**). The segmental cosine curve of the angle "θ" is also overlaid in **Figure 5** as a dotted line.

It can be seen that the power harvesting densities under a parameter of the angle "θ" fit well with the cosine curve of the angle "θ", which can be treated as the most obvious consequent as if Lambert's cosine law held good. At any rate, an automatic control of the angle "θ" around 0 degree without any power consuming devices is checked up to one of the most essential qualifications for high-efficiency in this piezoelectric power harvester driven by the wind-force, proclaiming one upgrading idea later on together with other future strategies.

3.4. Practical Demonstrations

Figure 6 shows the power harvesting densities versus the natural wind speeds. Though the power harvesting densities are scarcely high, the most significant benefit locates power harvesting proofs from the natural wind with low mean speeds down to about 0.6 m/s, which is quite low with missing in surveys [2]-[22] [29] [30] [31] [32] [33].

The power harvesting densities tend to be directly proportional to the natural wind speeds, indicating with a gray rod derived by least mean square approximation in Figure 6. Extrapolation of this gray rod informs that the cut-in wind speed of this piezoelectric power harvester is also quite low as about 0.4 m/s, signifying strong uniquity of this system.

Here, the obtained power harvesting densities from the natural wind are tremendously scattering. Such scattering data can be explained by ever-varying directions of the natural wind towards the fixed apparatus with the "wind-collector" concave side facing the outside as described in Section 2.2. Hence, automatic control of the angle "θ" around 0 degree without any power consuming devices is reconfirmed one of the most essential qualifications as stated in Section 3.3.

3.5. Future Strategies for Practical Applications

Simplicity and uniquity of this piezoelectric power harvester via the acoustic-pressures driven by the wind-forces are considered unobjectionable through the past chapters and sections. Remains for practical applications of this piezoelectric power harvester are all illustrated in Figure 7, exhibiting its scale flexibility at a glance.

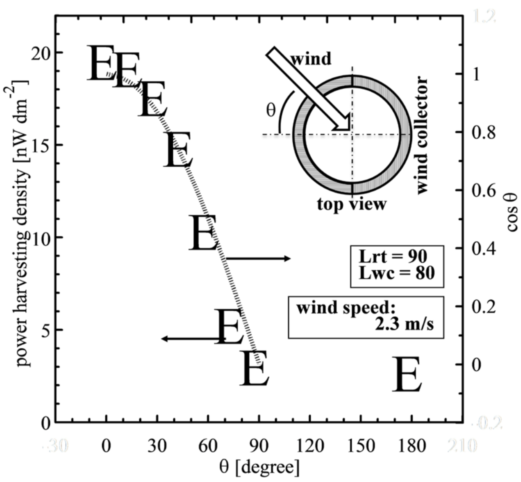

Figure 5. Effect of angle bwtween apparatus and fun (*i.e.* "θ") on power harvesting density.

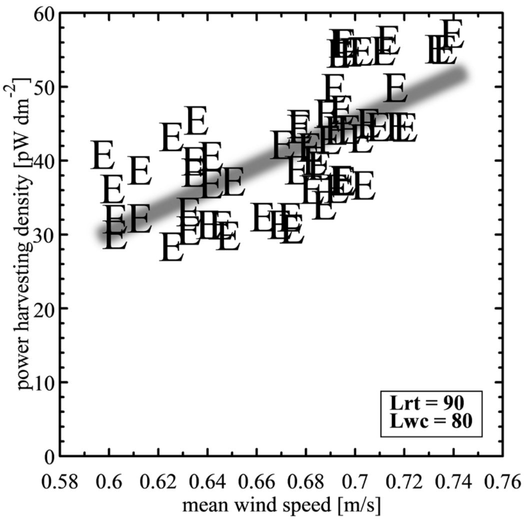

Figure 6. Power harvesting densities with natural winds.

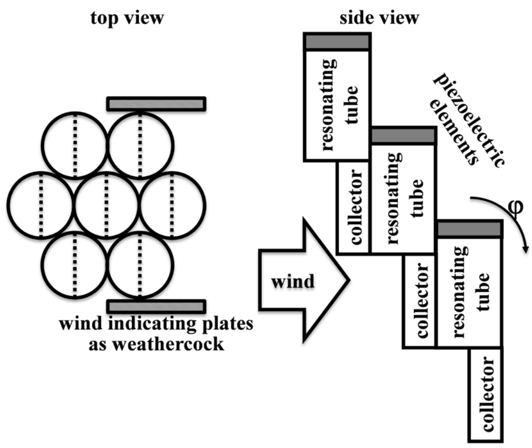

Figure 7. Multi-bundle pendant-type piezoelectric power harvester.

Comparing to the prototype apparatus (see Figure 1 and Figure 2), each tube constituting this multi-bundle pendant-type piezoelectric power harvester turns upside down. This is the simplest measure for protecting this piezoelectric power harvester from suspended particulate matters, small insects, bird's dropping, weather such as rain and snow, etc.

For controlling the angle "θ" around 0 automatically (see Figure 2 and Figure 5), installations of wind indicating plates leeward are considered effective. Meanwhile, further improved power harvesting densities are spontaneous if this piezoelectric power harvester could roll in "φ" direction as illustrated on the rightmost in Figure 7 because the natural wind blows in any direction. Automatic adjusting technique of "φ" is now under consideration.

Such configurations as illustrated in Figure 7 are able to provide so many advantages as design freedom, scale flexibility, ease of maintenance and readily manufactures. Since optimal design of this multi-bundle pendant-type piezoelectric power harvester via the acoustic-pressures driven by the wind-forces depends on wide-ranging factors such as its surrounding geography, collateral conditions and permissible footprint, numerical simulations and referring the literatures are exceedingly helpful [15] [30] [31] [34] [35].

4. Conclusions

In order to supplement all drawbacks of the extant power harvestings driven by wind-induced-air-column-resonations (*i.e.* acoustic-pressures), the piezoelectric power harvester via acoustic-pressures driven by low-speed wind-forces with the resonating-tubes and the wind-collectors was invented.

The champion power harvesting density of 19.5 nW/dm^2 could be procured at the wind speed of 2.3 m/s, the optimal resonating-tube length of 90 mm and the optimal wind-collector length of 80 mm. This utmost simple piezoelectric power harvester was found to possess another usage as the resonant frequency detector.

Power harvesting proofs from the natural wind down to about 0.6 m/s were successfully obtained. The cut-in wind speed of the prototype piezoelectric power harvester was found to be about 0.4 m/s.

Finally, the multi-bundle pendant-type piezoelectric power harvester via the acoustic-pressures driven by the wind-forces was specifically presented together with the solid and multiple strategies for practical applications.

Acknowledgements

Seiichi Deguchi would like to express deep gratitude to the late Mr. Tatsumi Imura for his kindhearted encouragements and helpful suggestions until his passing.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Howey, D.A., Bansal, A. and Holmes, A.S. (2011) Design and Performance of a Centimetre-Scale Shrouded Wind Turbine for Energy Harvesting. *Smart Materials and Structures*, **20**, R1-R12. https://doi.org/10.1088/0964-1726/20/8/085021

[2] Khan, A., Abas, Z., Kim, H.S. and Oh, I.K. (2016) Piezoelectric Thin Films: An Integrated Review of Transducers and Energy Harvesting. *Smart Materials and Structures*, **25**, R1-R16. https://doi.org/10.1088/0964-1726/25/5/053002

[3] Nabavi, S. and Zhang, L. (2016) Wind Energy Harvesters for Low-Power Applications: A Survey. *Sensors*, **16**, 1101-1131. https://doi.org/10.3390/s16071101

[4] Zhao, L. and Yang, Y. (2017) Toward Small-Scale Wind Energy Harvesting: Design, Enhancement, Performance Comparison, and Applicability. *Shock and Vibration*, **2017**, R1-R31. https://doi.org/10.1155/2017/3585972

[5] Bae, J., Lee, J., Kim, S.M., Ha, J., Lee, B.S., Park, Y.J., Choong, C., Kim, J.B., Wang, Z.L., Kim, H.Y., Park, J.J. and Chung, U.I. (2014) Flutter-Driven Triboelectrification for Harvesting Wind Energy. *Nature Communications*, **5**, 1-9. https://doi.org/10.1038/ncomms5929

[6] McCarthy, J.M., Watkins, S., Deivasigamani, A. and John, S.J. (2016) Fluttering Energy Harvesters in the Wind: A Review. *Journal of Sound and Vibration*, **361**, 355-377. https://doi.org/10.1016/j.jsv.2015.09.043

[7] Truitt, A. and Mahmoodi, S.N. (2013) A Review on Active Wind Energy Harvesting Designs. *International Journal of Precision Engineering and Manufacturing*, **14**, 1667-1675. https://doi.org/10.1007/s12541-013-0226-4

[8] Ovejas, V.J. and Cuadras, A. (2011) Multimodal Piezoelectric Wind Energy Harvesters. *Smart Materials and Structures*, **20**, R1-R9. https://doi.org/10.1088/0964-1726/20/8/085030

[9] Zhao, L., Tang, L. and Yang, Y. (2013) Comparison of Modeling Methods and Parametric Study for a Piezoelectric Wind Energy Harvester. *Smart Materials and Structures*, **22**, R1-R12. https://doi.org/10.1088/0964-1726/22/12/125003

[10] Sirohi, J. and Mahadik, R. (2011) Piezoelectric Wind Energy Harvester for Low-Power Sensors. *Journal of Intelligent Material Systems and Structures*, **22**, 2215-2228. https://doi.org/10.1177/1045389X11428366

[11] Zhao, L., Tang, L. and Yang, Y. (2012) Small Wind Energy Harvesting from Galloping Using Piezoelectric Materials. *ASME Conference on Smart Materials—Adaptive Structures and Intelligent Systems*, **2**, 919-927.

[12] Akayd, H.D., Elvin, N. and Andreopoulos, Y. (2010) Wake of a Cylinder: A Paradigm for Energy Harvesting with Piezoelectric Materials. *Experiments in Fluids*, **49**, 291-304. https://doi.org/10.1007/s00348-010-0871-7

[13] Vatansever, D., Hadimani, R.L., Shah, T. and Siores, E. (2011) An Investigation of Energy Harvesting from Renewable Sources with PVDF and PZT. *Smart Materials and Structures*, **20**, Article ID: 055019. https://doi.org/10.1088/0964-1726/20/5/055019

[14] Ji, J., Kong, F., He, L., Guan, Q. and Feng, Z. (2010) Piezoelectric Wind-Energy-Harvesting Device with Reed and Resonant Cavity. *Japanese Journal of Applied Physics*, **49**, Article ID: 050204. https://doi.org/10.1143/JJAP.49.050204

[15] Jung, H.J., Kim, I.H. and Jang, S.J. (2011) An Energy Harvesting System Using the Wind-Induced Vibration of a Stay Cable for Powering a Wireless Sensor Node. *Smart Materials and Structures*, **20**, Article ID: 75001. https://doi.org/10.1088/0964-1726/20/7/075001

[16] Kim, I.H., Seon, J.J.J. and Hyung, J.J. (2013) Performance Enhancement of a Rotational Energy Harvester Utilizing Wind-Induced Vibration of an Inclined Stay Cable. *Smart Materials and Structures*, **22**, R1-R7. https://doi.org/10.1088/0964-1726/22/7/075004

[17] Akaydin, H.D., Elvin, N. and Andreopoulos, Y. (2012) The Performance of a Self-Excited Fluidic Energy Harvester. *Smart Materials and Structures*, **21**, R1-R13. https://doi.org/10.1088/0964-1726/21/2/025007

[18] Imaizumi, S., Banno, H., Kato, H., Miwa, S., Takagi, K., Inoue, T., Nozoe, T., Saito, S., Sano, T., Nakai, Y., Sawada, K., Tsuge, J., Tokutake, K., Isu, N. and Deguchi, S. (2013) Theoretical and Experimental Verifications of Proposed Piezoelectric Power Generator Harvesting Waste Heat. *Proceedings of the International Symposium on EcoTopia Science*, 13-15 December 2013, 3-9.

[19] Kato, H., Banno, H., Yamada, A., Imaizumi, S., Miwa, S., Sawada, K., Tsuge, J., Tokutake, K., Takagi, K., Inoue, T., Nozoe, T., Saito, S., Sano, T., Nakai, Y., Isu, N. and Deguchi, S. (2013) Proposal and Experimental Verifications of Piezoelectric Power Generator Due to Pressure Fluctuations of Water/Low-Boiling Temperature Medium. *Proceedings of the International Symposium on EcoTopia Science*, 13-15

December 2013, 3-11.

[20] Shimasaki, S., Banno, H., Ogawa, M., Ito, M., Inoue, T., Takagi, K., Nozoe, T., Saito, S., Sano, T., Deguchi, S. and Isu, N. (2013) Proposal and Cold-Model Feasibility Study of New Piezoelectric Power Harvesting Process from Low-Temperature Waste Heats Induced by Vapor Pressure in Airtight Chamber. *Proceedings of the International Symposium on EcoTopia Science*, Nagoya, 13-15 December 2013, 12-20.

[21] Shimasaki, S., Banno, H., Ogawa, M., Ito, M., Miwa, S., Sawada, K., Inoue, T., Takagi, K., Deguchi, S., Saito, S., Sano, T., Nozoe, T. and Isu, N. (2013) Piezo-Electric Power Harvesting Device. *Japanese Open Patent*, No. 2013, Article ID: 158138.

[22] Zhao, J., Ramadass, Y., Lang, J., Ma, J. and Buss, D. (2013) Bias-Flip Technique for Frequency Tuning of Piezo-Electric Energy Harvesting Devices. *Journal of Low Power Electronics and Applications*, **3**, 194-214. https://doi.org/10.3390/jlpea3020194

[23] Khan, F.U. and Izhar (2015) State of the Art in Acoustic Energy Harvesting. *Journal of Micromechanics and Microengineering*, **25**, R1-R13. https://doi.org/10.1088/0960-1317/25/2/023001

[24] Li, B., You, J.H. and Kim, Y.J. (2013) Low Frequency Acoustic Energy Harvesting Using PZT Piezoelectric Plates in a Straight Tube Resonator. *Smart Materials and Structures*, **22**, R1-R9. https://doi.org/10.1088/0964-1726/22/5/055013

[25] Pillai, M.A. and Deenadayalan, E. (2014) A Review of Acoustic Energy Harvesting. *International Journal of Precision Engineering and Manufacturing*, **15**, 949-965. https://doi.org/10.1007/s12541-014-0422-x

[26] Sun, K.H., Kim, J.E., Kim, J. and Song, K. (2017) Sound Energy Harvesting Using a Doubly Coiled-Up Acoustic Metamaterial Cavity. *Smart Materials and Structures*, **26**, R1-R9. https://doi.org/10.1088/1361-665X/aa724e

[27] Ciaramella, A., Lauro, E.D., Martino, S.D., Falanga, M. and Tagliaferri, R. (2011) Modeling and Generating Organ Pipes Self-Sustained Tones by Using ICA. *Journal of Signal and Information Processing*, *Scientific Research*, **2**, 141-151. https://doi.org/10.4236/jsip.2011.23018

[28] Nederveen, C.J. and Dalmont, J.P. (2004) Pitch and Level Changes in Organ Pipes Due to Wall Resonances. *Journal of Sound and Vibration*, **271**, 227-239. https://doi.org/10.1016/S0022-460X(03)00643-6

[29] Sun, D., Xu, Y., Chen, H., Shen, Q., Zhang, X. and Qiu, L. (2013) Acoustic Characteristics of a Mean Flow Acoustic Engine Capable of Wind Energy Harvesting: Effect of Resonator Tube Length. *Energy*, **55**, 361-368. https://doi.org/10.1016/j.energy.2013.03.071

[30] Sun, D., Xu, Y., Chen, H., Wu, K., Liu, K. and Yu, Y. (2012) A Mean Flow Acoustic Engine Capable of Wind Energy Harvesting. *Energy Conversion and management*, **63**, 101-105. https://doi.org/10.1016/j.enconman.2011.12.035

[31] Yu, Y.S.W., Sun, D., Zhang, J., Xu, Y. and Qi, Y. (2017) Study on a Pi-Type Mean Flow Acoustic Engine Capable of Wind Energy Harvesting Using a CFD Model. *Applied Energy*, **189**, 602-612. https://doi.org/10.1016/j.apenergy.2016.12.022

[32] Lee, H.Y. and Choi, B. (2013) A Multilayer PVDF Composite Cantilever in the Helmholtz Resonator for Energy Harvesting from Sound Pressure. *Smart Materials and Structures*, **22**, R1-R12. https://doi.org/10.1088/0964-1726/22/11/115025

[33] Cepnik, C., Lausecker, R. and Wallrabe, U. (2013) Review on Electrodynamic Energy Harvesters—A Classification Approach. *Micromachines*, **4**, 168-196.

https://doi.org/10.3390/mi4020168

[34] Sousa, V.C., Anicézio, M.M., Marqui, C.D. and Erturk, A. (2011) Enhanced Aeroelastic Energy Harvesting by Exploiting Combined Nonlinearities: Theory and Experiment. *Smart Materials and Structures*, **20**, Article ID: 094007. https://doi.org/10.1088/0964-1726/20/9/094007

[35] Wu, Y., Li, D., Xiang, J. and Ronch, A.D. (2016) A Modified Airfoil-Based Piezoaeroelastic Energy Harvester Withdouble Plunge Degrees of Freedom. *Theoretical & Applied Mechanics Letters*, **6**, 244-247. https://doi.org/10.1016/j.taml.2016.08.009