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Application of Low-Cost Transducers for Indirect In-Cylinder Pressure Measurements

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Abstract

The aim of this work is to present the results achieved in the evaluation of combustion metrics using low-cost sensors for the indirect measurement of cylinder pressure. The developed transducers are piezoelectric rings placed under the spark plugs. Tests were carried out on three different engines running in various speed and load conditions. The article shows the characteristics of the signals generated by the piezo-ring sensors, compared to those coming from laboratory-grade pressure transducers: focus is to assess the achievable accuracy in the determination of frequently used combustion metrics, such as those related to knock intensity (Maximum Amplitude of Pressure Oscillations, MAPO), combustion phasing (MFB_{10}, MFB_{50}, ...), and peak pressure. Despite some issues related to the variation in sensitivity (temperature effect) to mechanical noise at high engine speeds and to signal deviation from the actual cylinder pressure trace in some portions of the engine cycle, the article shows that combustion metrics evaluated using low-cost sensors are meant to be used for combustion feedback control.

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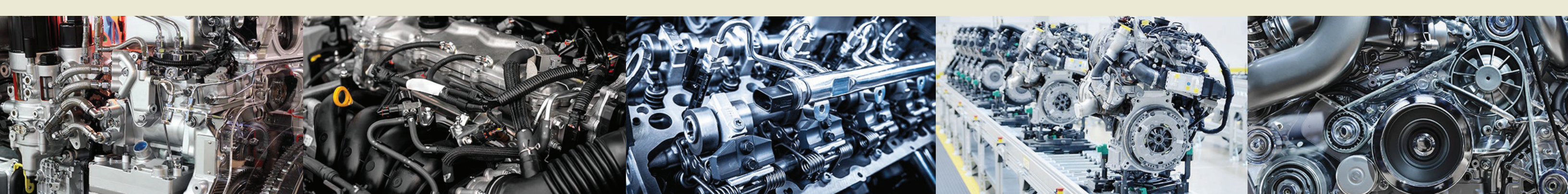

(2010): 1420-1429, https://doi.org/10.1016/j.ijhydene.2009.11.090.

38. Verhelst, S. and Wallner, T., "Hydrogen-Fueled Internal Combustion Engines," *Progress in Energy and Combustion Science* 35, no. 6 (2009): 490-527, https://doi.org/10.1016/j.pecs.2009.08.001.
39. Nakai, E., Goto, T., Ezumi, K., Tsumura, Y. et al., "Mazda Skyactiv-X 2.0 L Gasoline Engine," Presented at in *28th Aachen Colloquium Automobile and Engine Technology*, Aachen, 2019, 55-78.
40. Li, H. and Karim, G.A., "Knock in Spark Ignition Hydrogen Engines," *International Journal of Hydrogen Energy* 29, no. 8 (2004): 859-865, https://doi.org/10.1016/j.ijhydene.2003.09.013.
41. Szwaja, S., Bhandary, K.R., and Naber, J.D., "Comparisons of Hydrogen and Gasoline Combustion Knock in a Spark Ignition Engine," *International Journal of Hydrogen Energy* 32, no. 18 (2007): 5076-5087, https://doi.org/10.1016/j.ijhydene.2007.07.063.
42. Ravaglioli, V., Carra, F., Moro, D., De Cesare, M. et al., "Remote Sensing Methodology for the Closed-Loop Control of RCCI Dual Fuel Combustion," SAE Technical Paper 2018-01-0253, 2018, https://doi.org/10.4271/2018-01-0253.
43. Carlucci, A.P., Laforgia, D., Motz, S., Saracino, R. et al., "Advanced Closed Loop Combustion Control of a LTC Diesel Engine Based on In-Cylinder Pressure Signals," *Energy Conversion and Management* 77 (2014): 193-207, https://doi.org/10.1016/j.enconman.2013.08.054.
44. De Cesare, M., Ravaglioli, V., Carra, F., and Stola, F., "Review of Combustion Indexes Remote Sensing Applied to Different Combustion Types," SAE Technical Paper 2019-01-1132, 2019, https://doi.org/10.4271/2019-01-1132.
45. Ponti, F., "Indicated Torque Estimation Using a Torsional Behavior Model of the Engine," SAE Technical Paper 2005-01-3761, 2005, https://doi.org/10.4271/2005-01-3761.
46. Cavina, N., Sgatti, S., Cavanna, F., and Bisanti, G., "Combustion Monitoring Based on Engine Acoustic Emission Signal Processing," SAE Technical Paper 2009-01-1024, 2009, https://doi.org/10.4271/2009-01-1024.
47. Fiorini, N., Romani, L., Bellissima, A., Vichi, G. et al., "An Indirect In-Cylinder Pressure Measurement Technique Based on the Estimation of the Mechanical Strength Acting on an Engine Head Screw: Development and Assessment," *Energy Procedia* 148 (2018): 695-702, https://doi.org/10.1016/j.egypro.2018.08.159.
48. Teitelbaum, B.R. and Carrico, J.P., Integrated spark plug-combustion pressure sensor. US Patent 4,169,388, December 13, 1978.
49. Randall, K. and Powell, J., "A Cylinder Pressure Sensor for Spark Advance Control and Knock Detection," SAE Technical Paper 790139, 1979, https://doi.org/10.4271/790139.
50. Shimasaki, Y., Kobayashi, M., Sakamoto, H., Ueno, M. et al., "Study on Engine Management System Using In-Cylinder Pressure Sensor Integrated with Spark Plug," SAE Technical Paper 2004-01-0519, 2004, https://doi.org/10.4271/2004-01-0519.
51. Fiorini, N., Romani, L., Ferrara, G., Vichi, G. et al., "A Methodology for the Estimation of In-Cylinder Pressure in a Four-Stroke Internal Combustion Engine Based on the Combination of a Strain Washer Signal with a 0D Thermodynamic Model," *AIP Conference Proceedings* 2191 (2019): 020073, https://doi.org/10.1063/1.5138806.
52. Corti, E., Abbondanza, M., Ponti, F., and Raggini, L., "The Use of Piezoelectric Washers for Feedback Combustion Control," *SAE Int. J. Adv. & Curr. Prac. in Mobility* 2, no. 4 (2020): 2217-2228, https://doi.org/10.4271/2020-01-1146.
53. Fukuoka, T., *Threaded Fasteners for Engineers and Design—Solid Mechanics and Numerical Analysis* (Corona Publishing Co Ltd., Japan, 2015)
54. Shigley, J.E. and Mischke, C.R., *Standard Handbook of Machine Design*, 2nd ed. (New York: McGrawHill, 1996), 727-729.
55. Zakarian, D., Khachatrian, A., and Firstov, S., "Universal Temperature Dependence of Young's Modulus," *Metal Powder Report* 74, no. 4 (2019): 204-206, https://doi.org/10.1016/j.mprp.2018.12.079.
56. Singh, P.P. and Munish Kumar, F., "Temperature Dependence of Bulk Modulus and Second-Order Elastic Constants," *Physica B: Condensed Matter* 344, no. 1-4 (2004): 41-51, https://doi.org/10.1016/j.physb.2003.07.012.
57. Rajaram, G., Kumaran, S., and Srinivasa Rao, T., "High Temperature Tensile and Wear Behaviour of Aluminum Silicon Alloy," *Materials Science and Engineering: A* 528, no. 1 (2010): 247-253, https://doi.org/10.1016/j.msea.2010.09.020.
58. Herrmann, J., Inden, G., and Sauthoff, G., "Deformation Behaviour of Iron-Rich Iron-Aluminium Alloys at High Temperatures," *Acta Materialia* 51, no. 11 (2003): 3233-3242, https://doi.org/10.1016/S1359-6454(03)00144-7.
59. Maurya, R.K., *Characteristics and Control of Low-Temperature Combustion Engines* (Cham, Switzerland: Springer International Publishing, 2018), http://doi.org/10.1007/978-3-319-68508-3.
60. Ravaglioli, V. and Bussi, C., "Model-Based Pre-Ignition Diagnostics in a Race Car Application," *Energies, MDPI, Open Access Journal* 12(12):1-12, June 2019, https://doi.org/10.3390/en12122277.
61. Heywood, J.B., *Internal Combustion Engine Fundamentals* (New York: McGraw Hill Professionals, 2018), ISBN:1260116115.
62. Shimasaki, Y., Kobayashi, M., Sakamoto, H., Ueno, M. et al., "Pressure Sensor Integrated with Spark Plug," SAE Technical Paper 2004-01-0519, 2004, https://doi.org/10.4271/2004-01-0519.

63. Sawamoto, K., Kawamura, Y., Kita, T., and Matsushita, K., "Individual Cylinder Knock Control by Detecting Cylinder Pressure," SAE Technical Paper 871911, 1987, https://doi.org/10.4271/871911.
64. Morris, J., "Intra-Cylinder Combustion Pressure Sensing," SAE Technical Paper 870816, 1987, https://doi.org/10.4271/870816.
65. Corrigan, D. and Fontanesi, S., "Knock: A Century of Research," *SAE Int. J. Engines* 15, no. 1 (2022): 57-127, https://doi.org/10.4271/03-15-01-0004.
66. Zhen, X., Yang, W., Xu, S., Zhu, Y. et al., "The Engine Knock Analysis—An Overview," *Applied Energy* 92 (2012): 628-636, https://doi.org/10.1016/j.apenergy.2011.11.079.
67. Bengisu, T., "Computing the Optimum Knock Sensor Locations," SAE Technical Paper 2002-01-1187, 2002, https://doi.org/10.4271/2002-01-1187.
68. Horner, T., "Knock Detection Using Spectral Analysis Techniques on a Texas Instruments TMS320 DSP," SAE Technical Paper 960614, 1996, https://doi.org/10.4271/960614.
69. Corrigan, D.J., Breda, S., and Fontanesi, S., "A Simple CFD Model for Knocking Cylinder Pressure Data Interpretation: Part 1," SAE Technical Paper 2021-24-0051, 2021, https://doi.org/10.4271/2021-24-0051.
70. Cavina, N., Rojo, N., Businaro, A., and Cevolani, R., "Comparison between Pressure- and Ion-Current-Based Closed-Loop Combustion Control Performance," *SAE Int. J. Engines* 12, no. 2 (2019): 219-230, https://doi.org/10.4271/03-12-02-0016.
71. Gail, S., Cracknell, R.F., Corrigan, D., Festa, A. et al., "Evaluating a Novel Gasoline Surrogate Containing Isopentane Using a Rapid Compression Machine and an Engine," *Proceedings of the Combustion Institute* 38, no. 4 (2021): 5643-5653, https://doi.org/10.1016/j.proci.2020.07.103.
72. Scocozza, G., Silvagni, G., Brusa, A., Cavina, N. et al., "Development and Validation of a Virtual Sensor for Estimating the Maximum In-Cylinder Pressure of SI and GCI Engines," SAE Technical Paper 2021-24-0026, 2021, https://doi.org/10.4271/2021-24-0026.
73. Brusa, A., Cavina, N., Rojo, N., Mecagni, J. et al., "Development and Experimental Validation of an Adaptive, Piston-Damage-Based Combustion Control System for SI Engines: Part 1—Evaluating Open-Loop Chain Performance," *Energies* 14 (2021): 5367, https://doi.org/10.3390/en14175367.

Appendix

This section shows the technical characteristics of the reference sensors and piezoelectric washer used for each engine.

TABLE A.1 Technical data of reference sensor used on Engines 1-3.

M12 × 1.25 measuring spark plug with integrated 3 mm cylinder pressure sensor Type 6115C		
Manufacturer	**Kistler**	
Measuring range	bar	0 ... 200
Overload	bar	250
Sensitivity at 200°C	pC/bar	≈−10
Sensor operating temperature range	°C	−20 ... 350
Thermal sensitivity shift		
200 ± 50°C	%	<±1

TABLE A.2 Technical data of reference sensor used on Engine 2.

Water-cooled pressure sensor for combustion engines Type 6061C		
Manufacturer	**Kistler**	
Measuring range	bar	0 ... 250
Overload	bar	300
Sensitivity at 200°C	pC/bar	≈−26
Sensor operating temperature range (uncooled)	°C	−40 ... 350
Thermal sensitivity shift		
RT ... 350°C (uncooled)	%	±3
50°C ... ± 30°C (cooled)	%	±0.2

TABLE A.3 Technical data of piezoelectric washer sensor used on Engines 1, 2, 3.

M12-M10 piezoelectric washer		
Sensor thickness	mm	1.9 ... 2
Measuring range	bar	0 ... >300
Overload	bar	NA
Sensitivity at 100°C	pC/bar	70 ... 120
Sensor operating temperature range	°C	<175
Thermal sensitivity shift		
−20°C ... 125°C	%	0 ... 4