calculated by SolidWorks®. After we figure out the detailed design of the shaft, the connectors between the shaft and the winding, and the optical encoder we are going to use, a larger total rotor inertia is expected [21], as will be presented in a companion paper. Also note that the entries in the bottom three rows are not functions of the actuator alone, but of the actuator, the balance of the EMV, and the control strategy. These entries present each option as favourably as possible and the limited-angle actuator stands out with the low enough power consumption, fast enough transition, and small enough package.

Table V. Comparison of two commercial motors and the LA actuator.

	Brush motor (experiments)	Brushless motor (experiments)	LA actuator (simulation)
Size (mm*mm*mm)	69*69*119	28*28*90	28*36*60
Volume (mm^3/normalized)	566559/8	70560/1	64480/0.86
Rotor Inertia ($10^{-6}Kg\cdot m^2/s$ /normalized)	3.5/2.9	1.2/1	1.3/1.08
Winding Loss (W/normalized)	31/0.26	118/1	34/0.29
Power Consumption (W/normalized)	49/0.36	138/1	56/0.405
Transition Time (ms)	2.7	2.4	2.8

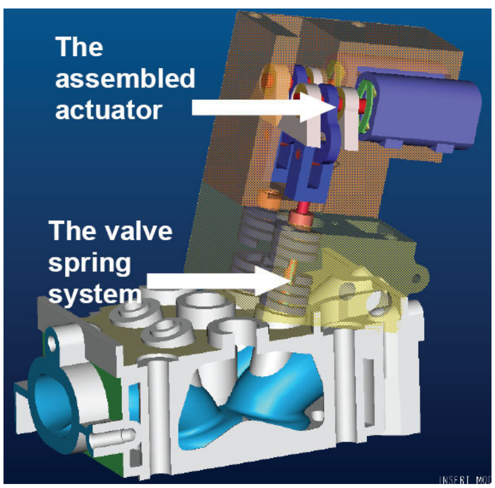

Fig. 13. Independent valve actuation system mounted on an engine head (courtesy to ITRI).

5 Conclusions

This paper addresses a custom-designed limited-angle actuator, which fits in an electromechanical valve drive to provide VVT in IC engines within a package small enough to fit in the limited space over the engine head, with a transition time fast enough to accommodate faster engine speed, and a low power consumption. The customized limited-angle actuator enabled the projection of independent valve actuation for a 4-cylinder 16-valve IC engine with reasonable power consumption and high engine speed.

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References

[1] M. B. Levin, and M. M. Schlecter, “Camless Engine”, *SAE Technical Paper Series*, Paper 960581, 1996.
[2] P. Barkan, et. al., “A Review of Variable Valve Timing Benefits and Modes of Operation,” *SAE Technical Paper Series*, Paper 891676, 1989.
[3] T. Ahmad, et, al., “A Survey of Variable-Valve-Actuation Technology,” *SAE Technical Paper Series*, Paper 891674, 1989.
[4] M. Pischinger, et. al., “Benefits of the Electromechanical Valve Train in Vehicle Operation,” SAE Technical Paper Series, Paper 2001-01-1223, 2001.
[5] C. Tai, et. al., “Increasing Torque Output from a Turodiesel with Camless Valve Train,” SAE Technical Paper Series, Paper 2002-01-1108, 2002.
[6] M. Sellnau, et. al., “Two-Step Variable Valve Actuation for Fuel Economy, Emissions, and Performance,” SAE Technical Paper Series, Paper 2003-01-0029, 2003.
[7] G. B. Parvate-Patil, et. al., “An Assessment of Intake and Exhaust Philosophies for Variable Valve Timing,” SAE Technical Paper Series, Paper 2003-32-0078, 2003.
[8] R. Steinberg, et. al., “A Fully Continuous Variable Cam Timing Concept for Intake and Exhaust Phasing”, SAE Technical Paper Series, Paper 980767, 1998.
[9] F. Pischinger, et. al., “Electromechanically Operating Actuators,” U.S. Patent 4,455,543, 1984.
[10] F. Pischinger, et. al., “Electromechanical Variable Valve Timing,” Automotive Engineering International, 1999.
[11] M. Gottschalk, “Electromagnetic Valve Actuator Drives Variable Valvetrain,” Design News, November 1993.
[12] R. Flierl, and M. Klüting, “The Third Generation of Valvetrains --- New Fully Variable Valvetrains for Throttle-Free Load Control,” SAE Technical Paper Series, Paper 2000-01-1227, 2000.
[13] S. Butzmann, et. al., “Sensorless Control of Electromagnetic Actuators for Variable Valve Train,” SAE Technical Paper Series, Paper 2000-01-1225, 2000.
[14] K. Peterson, et. al., “Nonlinear Self-tuning control of Soft Landing of an Electromechanical Actuator,” Proc. 2nd IFAC Conference on Mechatronics Systems, Berkeley, CA, 2002.
[15] K. Peterson, et. al., “Rendering the electromechanical valve actuator globally asymptotically stable,” Proc. 42nd IEEE Conference Decision and Control, Maui, HI, Dec. 2003, pp. 1753–1758.
[16] D. Durrieu, et. al., “Electro-Magnetic Valve Actuation System: First Steps Toward Mass Production,” SAE Technical Paper Series, Paper 2008-01-1360, 2008.
[17] W. S. Chang, “An Electromechanical Valve Drive Incorporating a Nonlinear Mechanical Transformer,” Ph.D. thesis, Massachusetts Institute of Technology, 2003.
[18] T. A. Parlikar, “Experimental Implementation of an Electromagnetic Engine Valve”, Master Thesis, Massachusetts Institute of Technology, 2003.
[19] Y. H. Qiu, et. al., “Design and Experimental Evaluation of An Electromechanical Engine Valve Drive,” in Proceedings of the 35th IEEE Power Electronics Specialists Conference, pp. 4838-4843, Aachen, Germany, June, 2004.
[20] T. A. Parlikar, et. al., “Design and Experimental Implementation of an Electromagnetic Engine Valve Drive”, in IEEE/ASME Transaction on Mechatronics, Vol.10, NO.5, October 2005.
[21] Y. H. Qiu, “Advanced Modeling, Control, and Design of an Electromechanical Engine Valve Drive System with a Limited-angle Actuator,” Ph.D. thesis, Massachusetts Institute of Technology, 2009.
[22] Y. H. Qiu, et. al., “Optimal Cam Design and System Control for an Electromechanical Engine Valve Drive”, in proceedings of the.IEEE International Conference on Industrial Technology, 2010, accepted.