

STATIC AND DYNAMIC PERFORMANCE OF STACKED MULTILAYER ACTUATORS BASED ON HARD AND SOFT PZT

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Abstract:

The use of piezoelectric actuators has been steadily increasing in recent years. Piezoelectric actuators are now used in very diverse applications, e.g. fuel injection, printing, active noise and vibration control, piezo motors, piezo valves etc. Today, piezoelectric actuators are mainly manufactured by the multilayer approach, which has several advantages over the stacked type actuators, the most important being low voltage, high strain and low cost. Most suppliers of piezoelectric actuators offer high- d_{33} soft-doped PZT versions only. However, for some applications actuators based on other piezoelectric or electrostrictive materials are advantageous. A comparison of actuator performances has been carried out in order to provide data for a more appropriate selection of materials for piezoelectric actuators.

Introduction

In recent years, the range of applications for piezoelectric actuators has rapidly expanded. Traditionally, piezoelectric actuators have mainly been used for micro- and nanopositioning applications. However, due to the fact that multilayer actuators are now commercially available in multilayer low-voltage versions, various sizes, shapes and materials, piezoelectric actuators are now utilised in a much broader range of applications.

The typical material used in piezoelectric actuators is a soft-doped PZT well suited for micropositioning applications due to a high d_{33} constant. However, many new applications often require not only a high stroke, but sometimes that the piezoelectric actuators must work at high temperature, e.g. in fuel injection up to 200 °C, or must work at high frequency without significant heat generation, e.g. in ultrasonic motors operating at 20 – 30 kHz. Furthermore, in some applications the high permittivity of soft-doped PZT materials result in a very high capacitance of the piezoelectric actuators, thus requiring complicated driving electronics. Here, a hard-doped, low-permittivity PZT material offers significant advantages.

In addition to commercially available piezoelectric actuators, Ferroperm A/S have recently introduced actuators based on hard-doped PZT and PMN. To date, very limited information about properties of piezoelectric actuators based on hard-doped PZT has been available.

A study comparing the performance of piezoelectric actuators based on six of Ferroperm compositions was carried out in order to point out the advantages of the different actuator materials.

A number of stacked ceramic multilayer actuators, SCMA, with a cross section of 7 mm x 7 mm, a length of 40 mm and ceramic layer thickness of 100 µm were prepared by PZTech ApS, Table 1.

Table 1. Selected properties of the studied actuators.

Material	C (µF)	tan δ (%)	Max. stroke (µm)
Pz21	3,47	2,9	59
Pz24	0,51	0,6	28
Pz26	1,36	0,6	41
Pz27	1,81	2,9	72
Pz29	2,90	2,2	65
Es91	22	8,2	45

Pz21 and Pz29 are very soft PZT's, Pz27 a medium soft PZT, Pz24 and Pz26 hard PZT's and Es91 is a PMN-PT material.

The study of the SCMA's included:

- Strain at high field strength.
- Strain at high mechanical load.
- Hysteresis and creep.
- Actuator stiffness.
- Dielectric dissipation at dynamic conditions.

Actuator Performance, Static Conditions

The static performance of a piezoelectric actuator is influenced by several factors, which should be considered in applications, e.g. the available stroke (strain), hysteresis, creep, stiffness and load capability. Strain versus electrical field curves is shown in Fig. 1. For clarity, the curves are successively displaced by 0,1% on the Y- axis. Quite remarkable differences between the materials are seen. Pz24, Pz26 and Pz27 show a linear displacement, whereas Pz21, Pz29 and Es91 have an unlinear characteristic.

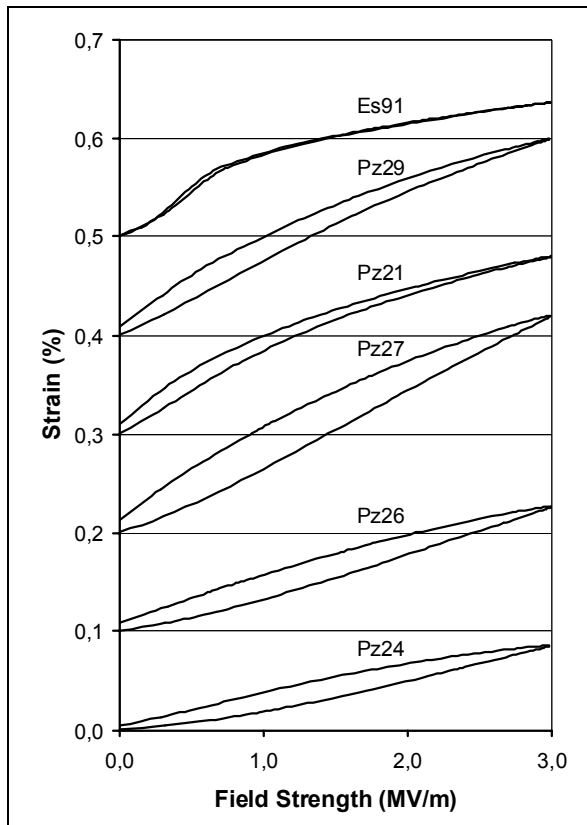


Fig. 1 DC d_{33} strain of actuator materials.

Table 2. Properties of actuator materials.

Material	Strain at 3 MV/m (%)	Hysteresis (%)	Young's modulus (GPa)
Pz21	0,180	11,4	61
Pz24	0,085	23,5	39
Pz26	0,126	19,9	45
Pz27	0,220	18,6	45
Pz29	0,199	12,5	47
Es91	0,136	4,4	82

Maximum strain and hysteresis levels have been estimated from the curves in Fig. 1, Table 2. The hysteresis is defined as the maximum vertical strain difference divided by the maximum strain. Charge coefficients, d_{33} , at high electrical field have been estimated from the strain data and a comparison with low-field d_{33} data is shown in Table 3. Especially Pz24, Pz26 and Pz27 materials have significantly higher d_{33} coefficients at high electrical field strength, and Pz27 even higher than the high-permittivity materials Pz21 and Pz29.

Table 3. d_{33} , low- and high-field values.

Material	d_{33} Low field (pm/V)	d_{33} High field (pm/V)
Pz21	640	600
Pz24	190	280
Pz26	290	420
Pz27	425	730
Pz29	575	660
Es91	-	450

The compression of all actuators when subjected to an increasing load has been characterised in Fig. 2.

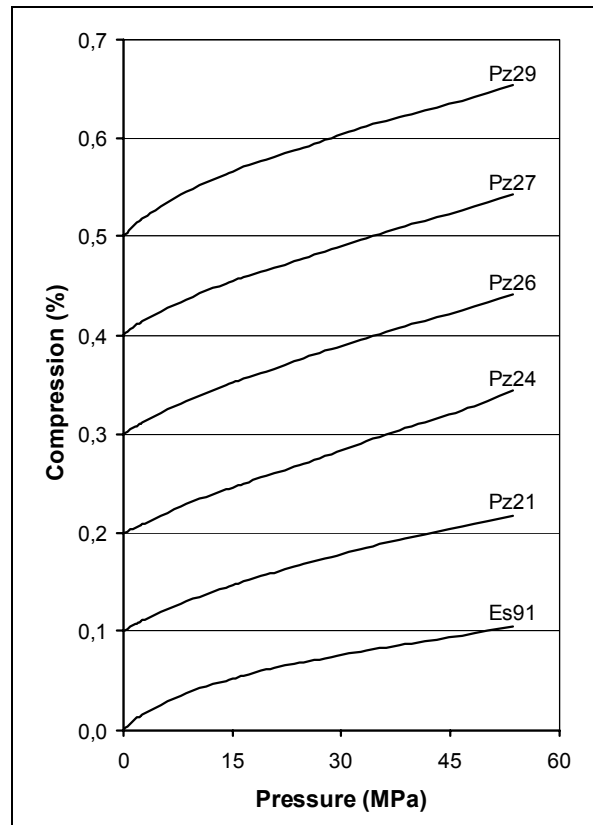


Fig. 2 Actuator stiffness.

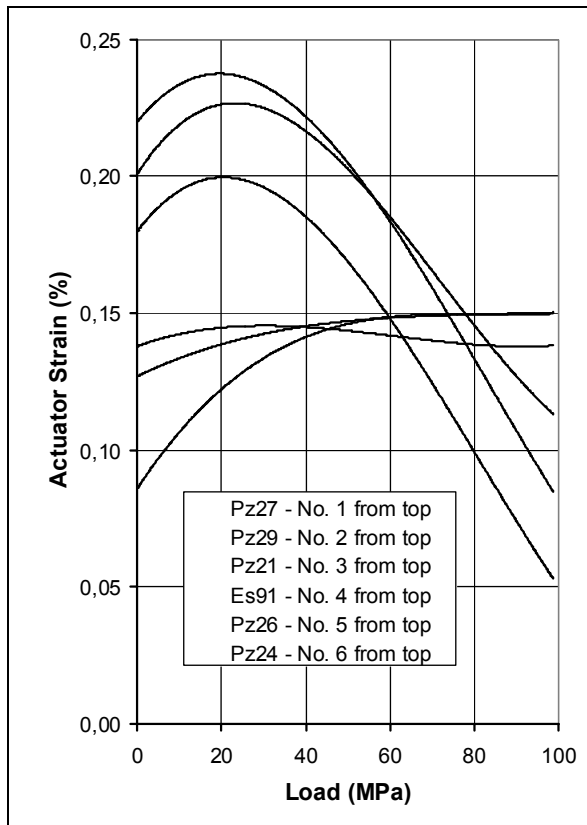


Fig. 3 Actuator strain versus pressure.

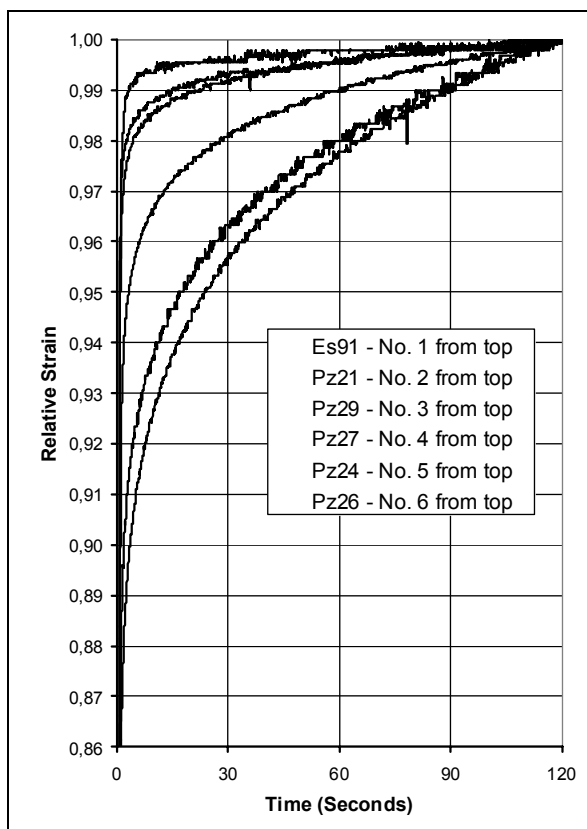


Fig. 4 Creep of actuator materials.

The first part of the compression, up to approximately 15 MPa, is not linear, which is explained by the lower stiffness of glue interfaces in the actuator stacks. At increasing loads, the curves become linear and this linear part of the curves has been used for estimation of Young's modulus, Table 2.

Actuator strain at increasing load is shown in Fig. 3. Most remarkable is the low influence of mechanical preload obtained for the hard-doped PZT materials, Pz24 and Pz26, and the electrostrictive PMN material, Es91.

The actuator materials have quite different creep behaviour. In Fig. 4 are shown the relative strain level upon charging of the actuators for 120 seconds. The Es91 material almost instantly reaches 99% strain. Also the high-permittivity materials Pz21 and Pz29 have low creep levels.

Actuator Performance, Dynamic Conditions

In dynamic applications, the maximum operating conditions, e.g. operating frequency and signal amplitude, are normally limited by heating of the actuators caused by dielectric losses. The power density P_d dissipated in the ceramic by dielectric dissipation is given by Formula 1.

$$(1) \quad P_d = 2\pi f E_{rms}^2 \epsilon_{33,r}^T \epsilon_0 \tan \delta \quad [W/m^3]$$

where E_{rms} is the rms electrical field.

The power dissipated per cubic meter can be estimated by Formula 1 for various actuator materials, Table 4.

Table 4. Dielectric dissipation estimated for 100 Hz operation and $E_{rms} = 1$ MV/m.

Material	$\epsilon_{33,r}^T$	$\tan \delta$	P_d (W/cm ³)
Pz21	3800	0,018	0,3805
Pz24	400	0,002	0,0045
Pz26	1300	0,003	0,0217
Pz27	1800	0,017	0,1702
Pz29	2900	0,019	0,3065
Es91	18000	0,080	8,0111

Normally, the dissipated power will cause the temperature of the material to rise. Both ϵ_{33}^T and $\tan \delta$ change with temperature and electrical field [1,2] and as such the power dissipated

will not remain constant with increasing temperature. In order to characterise the power dissipation of the different actuator materials all 6 actuators were tested at dynamic conditions. Figs. 5 and 6 show the temperature versus frequency for Pz26 and Pz27 stacks operated at positive electrical fields (E_{pp} , peak to peak) of 1, 2 and 3 MV/m. In order to ensure temperature equilibrium, all actuators were operated at steady conditions without cooling for 5 min. between temperature measurements.

The behaviour of Pz24 was very similar to that of Pz26. Pz21 and Pz29 had very similar behaviour to Pz27. Due to the very high capacitance of Es91, this material was not characterised at dynamic conditions. Figs. 5 and 6 show that maximum operating frequency decreases dramatically with increasing electrical field strength, as predicted by Formula 1.

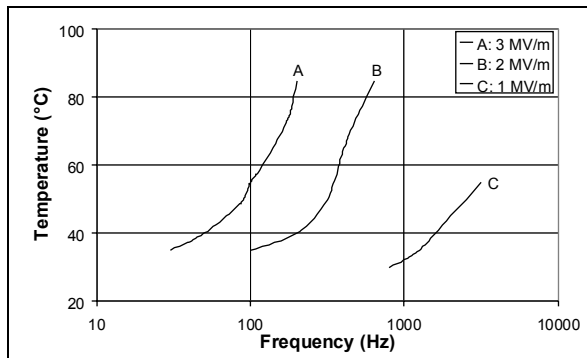


Fig. 5 Dynamic operation, Pz26

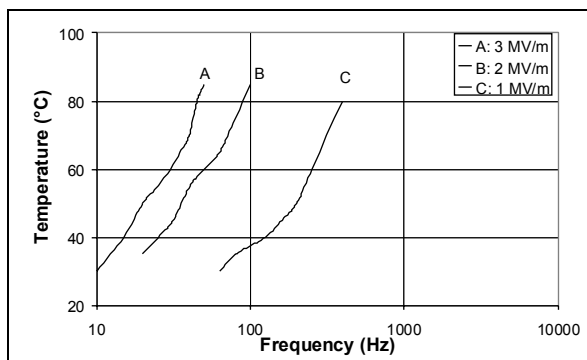


Fig. 6 Dynamic operation, Pz27

In Table 5, the operating frequency is given for 50 °C equilibrium at E_{pp} of 1, 2 and 3 MV/m.

From Figs. 5 and 6 and Table 5 it is evident that the hard-doped materials, Pz24 and Pz26, can be operated at 5 – 30 times higher frequency than the soft-doped materials, Pz21, Pz27 and Pz29.

Table 5. Operating frequency corresponding to 50°C.

Material	$E_{pp} =$ 1 MV/m	$E_{pp} =$ 2 MV/m	$E_{pp} =$ 3 MV/m
Pz21	80 Hz	40 Hz	28 Hz
Pz24	3700 Hz	370 Hz	125 Hz
Pz26	2550 Hz	320 Hz	110 Hz
Pz27	140 Hz	40 Hz	23 Hz
Pz29	135 Hz	40 Hz	32 Hz

A more practical comparison would be for equal vibration amplitude, which is shown in Fig. 7. Here, the Pz26 actuator was operated at 3 MV/m and the Pz27 actuator at 2 MV/m. The vibration amplitude at these respective electrical fields is similar for the two materials. Fig. 7 shows that twice the operating frequency can be obtained with a hard-doped PZT actuator material.

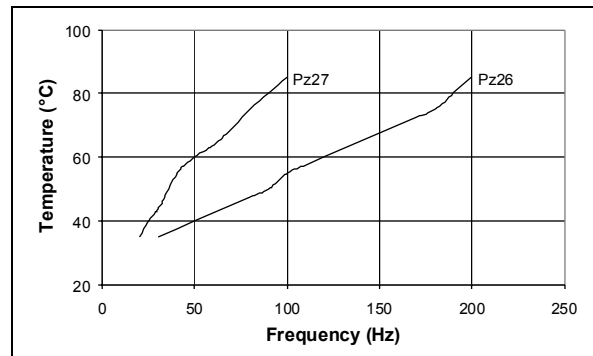


Fig. 7 Comparison at equal vibration amplitude.

Conclusion

The static and dynamic performance of six actuator materials has been compared. Important differences are seen underlining the advantages of choosing the appropriate actuator material for applications of piezoelectric actuators. Most notable is probably the remarkable difference at dynamic operation conditions seen for hard- and soft- doped PZT materials.

References

- [1] B. Andersen, E. Ringgaard, T. Bove, A. Albareda, R. Pérez. Performance of piezoelectric ceramic multilayer components based on hard and soft PZT. Actuator 2000.
- [2] Ferroperm Catalogue, 1995 issue.