

APPLICATION OF PIEZOELECTRIC MATERIALS IN TRANSPORTATION INDUSTRY

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Abstract

The present paper gives an overview on actual developments of the application of piezoelectric components in transportation industry.

During the last decades, piezoelectric materials made huge progress in entering commercial mass markets throughout all branches, where piezoelectrics are used as the basis materials for actuators as well as sensors. Especially in transportation industry, they found numerous fields of applications. The development of piezoelectric actuators for fuel injection systems is a popular application of the near past, active noise and vibration reduction is a current activity, and the use of piezoelectric materials for energy harvesting in vibrating structures is one possible future trend. Recent developments in ceramic processing and possibilities in tailoring of special properties will be shown as well as latest developments in manufacturing of piezoelectric actuator and sensor components. Another part of the paper is the aspect of reliability and performance degradation of piezo-based active systems, as well as new concepts of structural health monitoring. Selected applications will be explained and discussed in detail elucidating the multiple possibilities of these materials especially in transportation industries.

Introduction

Applications of piezoelectric materials have expanded into many fields since the discovery of the effect by the Curie brothers in 1880-1881. An overview on the manifold applications is given in [1, 2]. Lead-Zirconate – Titanate (PZT) ceramics, which were discovered in 1954 and replaced barium titanate ceramics in all fields of piezoelectric applications, became the material dominating the world market until today [3].

Piezoelectric devices fit into four general categories, depending of what type of physical effect is used: *generators, sensors, actuators, and transducers*. Generators and sensors make use of the direct piezoelectric effect, meaning that mechanical energy is transformed into a dielectric displacement. This, in turn, is measurable as a charge or voltage signal between the metallised surfaces of the piezoelectric material. Actuators work vice-versa when transforming electrical energy into mechanical by means of the inverse piezoelectric effect. Finally, in transducers both effects are used within one and the same device. For all of these basic functionalities, different designs are available. A good overview on the different design types and possibilities for applications is found in [4]. Table 1 summarizes the different effects and the designs which are candidates for application in transportation industry.

Table 1: Applications of piezoelectric materials and designs

Design/ effect direction	Direct piezoeffect		Indirect piezoeffect	Both effects transducer
	Sensor	Generator	Actuator	
<i>Bulk material</i> (d_{33} – effect)	Accelerometers Knock sensors Pressure/Force sensor	High voltage spark igniters	-	Ultrasonic sonar devices Distance meters Ultrasonic materials charac-terisation
<i>Multilayer</i> (d_{33} – effect)	-	Energy harvesting	Active Vibration Reduction Nano – Positioning High–force–actuation	-
<i>Patch (monolithic)</i> (d_{31} – effect)	Dynamic strain sensor	Energy harvesting	Active Vibration Reduction	-
<i>Patch (fibre composites)</i> (d_{31} and d_{33} – effect)	Dynamic Strain sensors	Energy harvesting	Active Vibration Reduction	-
<i>Bi-/trimorph</i> d_{31} + bimorp effect	-	-	Textile machines Fans	-
<i>Special designs</i>	-	Cymbal trans- ducers for Energy harvesting	Ultrasonic Motors	Transformers

The physical properties of the device mainly depend on its constructive designs. Piezoelectric stack actuators, for instance, typically generate large forces of several kN and only small free strokes of some microns. The voltages necessary to drive the device is between several 100V and 1 kV, depending on the layer thickness. Bimorph actuators, on the other hand, generate low forces of some Newtons and free strokes of several mm. Piezoelectric patches are used as actuators, sensors or generators. Due to the lower stiffness of patches or fibre modules compared to stacks or bulk material, the forces generated by patch and fibre actuators are significantly lower. Their advantage is their applicability to flat structures. Fibre actuators and sensors have the additional advantage of being flexible and therefore show good adaptability to curved or uneven surfaces. A comprehensive overview on many types of actuators is given in [5].

The physical properties of the piezoelectric basis material itself depend on many factors. Today, it is possible to tailor the properties of the materials by dopants and so gaining a large variety in properties. Details on this topic are found in the books by Jaffe [6] and Uchino [7].

Current Applications of Piezoelectrics in Transportation Industry

The property of piezoelectric ceramics to withstand harsh environmental conditions present in automobiles made it a candidate material for application in all branches of transportation industry. The following are example applications of piezoelectrics in passenger cars, which are well documented in the literature and therefore only described in brief here:

Knock sensors are placed near the engine in order to detect irregular combustions [8]. The measurement principle is the one also used in accelerometers. The piezoelectric material is placed between the vibrating structure and a seismic mass introducing the vibration forces into the piezo element. The piezo element itself converts the vibrations into an electric charge proportional to the applied force. Usually, piezoelectric ceramics (PZT) with specially tailored properties are used. The material has to withstand high temperatures (up to 200°C) as well as rapid temperature changes. Also, the piezoelectric coefficient of the material must be almost independent of the temperature and remain stable over the vehicle's lifetime. Only recently, first attempts were made to replace PZT by thin PVDF foil sensors [9].

Distance sensors are ultrasonic transducers used in vehicles as so called parking pilots. During backing, the transducer emits ultrasonic waves reflected by the obstacle and then, in turn, changed into an electrical system by the same transducer now acting as an ultrasonic sensor. From the travelling time the distance is calculated [8].

Fuel injection systems based on piezoelectric stack actuators set another milestone in the piezo – technology [10]. The advantage compared to the conventional magnetic systems was the much faster response of the piezoelectric actuators and the possibility to drive any desired profile of valve displacement. It was not only that this technology reduced the fuel consumption by more than 20%, it was also that piezoelectric stack actuator technology as a whole experienced a decisive push [11]. One key issue the early development phases was the question of the reliability of the actuators under harsh engine environments [12].

Active Vibration Reduction: Automobile Oil Pan

Although the potential of piezoelectrics for AVC / ASAC applications has been shown in many studies before [13], there are still many practical obstacles hindering the introduction of such systems into mass markets. The example of the automotive oil pan, which is under intensive investigation in the EU Integrated Project “InMar” [14] shows the recent progress in solving these problems. In urban traffic, the most dominating noise source is the power engine itself and, in particular, the oil pan. [15], Fig. 1.

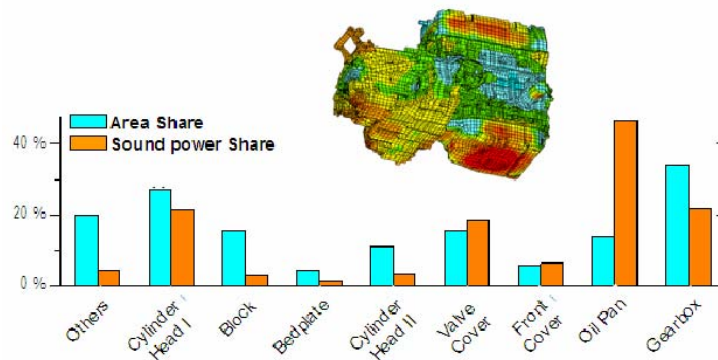


Fig. 1 Power train component noise contribution; comparison of near-field sound intensity analysis and combined FEM/MBS simulation (source: FEV) [15]

Therefore, the vibration reduction of thin wall structures by means of active materials is under intensive research. The identification of the most prominent oil pan natural vibration modes under real world engine excitation as well as the definition of sensor and actuator position are performed by means of combined Finite Element (FEM: structural behaviour) and Multi Body System (MBS: power train excitation) simulation. The comparison of vibration modes reveals that the simulation results correlate well to the experimental results, Fig. 2.

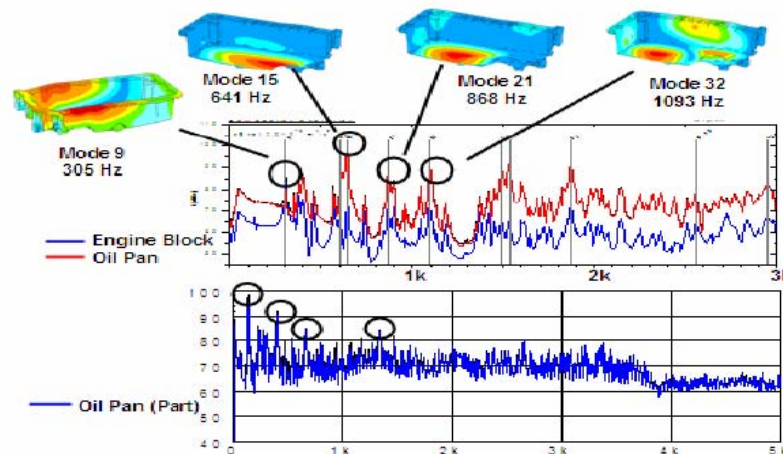


Fig. 2 Comparison of experimental and simulation results. Top: FEM simulation; Bottom: Near-field sound intensity analysis (source: FEV, AVL) [15]

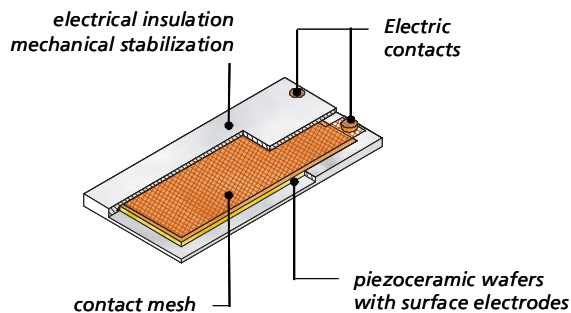
The most critical part in practical set up of the system is the choice of the actuator system. Here, piezoelectric patch actuators are used which will be attached to the surface of the oil pan.

First numerical and experimental investigations on a laboratory demonstrator at LBF showed that significant vibration reduction could be achieved. However, for later practical application, some important steps in research have to be carried out. In the following, the recent progress in these topics will be shown briefly:

High Temperature Piezocomposites

The development of high temperature piezoelectric actuator modules is essentially for the practical applicability of an active damping concept for the oil pan, since the oil temperature

raises the oil pan temperatures to well above 100°C. The technology to realize this challenging task was developed by the Institute of Composite Structures and Adaptronics of the German Aerospace Center (DLR). The principle design of such an actuator is shown in Fig. 3. The piezoceramic wafers are provided with uniformly metalized surfaces to operate in the lateral d_{31} -mode. The piezoceramic is embedded between thin layers of insulating material and layers with contacting structures. The contacting layer is made of a conductive flexible material (eg. copper mesh with a wire diameter of 0.03mm) having the shape and size of the piezoceramic wafer. The flexibility of the contacting material guarantees a long lifetime and reliability.



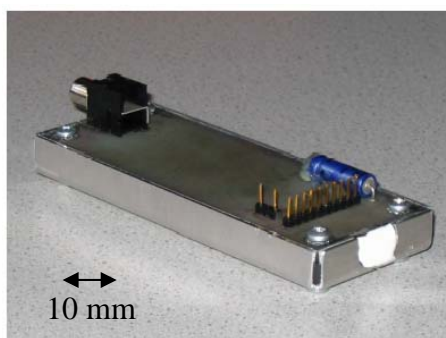
Basic properties of the High Temperature piezomodule:

Voltage range: 0 – 260 V
Max. temperature: 180 °C

Fig. 3 Principle device design, used for the development of high T_c – piezoelectric modules. The materials (PZT, Polymer, Electrodes) must be selected in view of a working temperature $T = 180$ °C. (Source: DLR)

Miniaturized Power - Electronics

Another main obstacle on the way towards AVR – systems for automotives is the question of the power amplification system. It must be compatible to the on-board electrical power supply, less space consuming, light, and robust against vibrations. Currently, such miniaturized power amplifiers for piezos are under investigation by the University of Twente [14]. The first prototypic design and basic properties of such amplifiers is shown in fig. 4. By using a novel aluminium housing and by filling the interior of the amplifiers with a polyurethane resin, the weight and the robustness as well as the self – heating during operation was dramatically improved.



Basic properties of the miniaturized amplifiers:

Gain 34.6 dB
Power supply: +300V / +30V
Frequency range: 40 .. 40 kHz
Size: ca. 10 x 3 x 2 cm
Weight: 100g
Energy dissipation during operation: 1,5W
Self heating max. temperature: 45°C

Fig. 4 Design and properties of the newly developed miniaturized electronics (source: University of Twente)

Health monitoring: Wear Detection of Train Wheels

Health monitoring and damage detection concepts have attracted many researches in the past [16, 17], especially with involvement of piezoelectric materials as the sensing elements [18]. Within the aforementioned project InMar [14], a new development is under research. This is a wear detection system for train wheels. The idea is to detect the changes in the vibration behaviour of the entire wheel caused by the surface changes on the rolling contact area, Fig. 5. Theoretical work on the vibration behaviour of train wheels encourage to choose this kind of method [19, 20]. Piezoelectric sensors are placed on distinct areas of the wheel, changing the displacements on the surface into electrical signals. The biggest problem is to adequately define the correlation between modal behaviour of the wheel and the measured signals as well as the sensitivity of the overall concept to the comparably small changes in modal parameters.

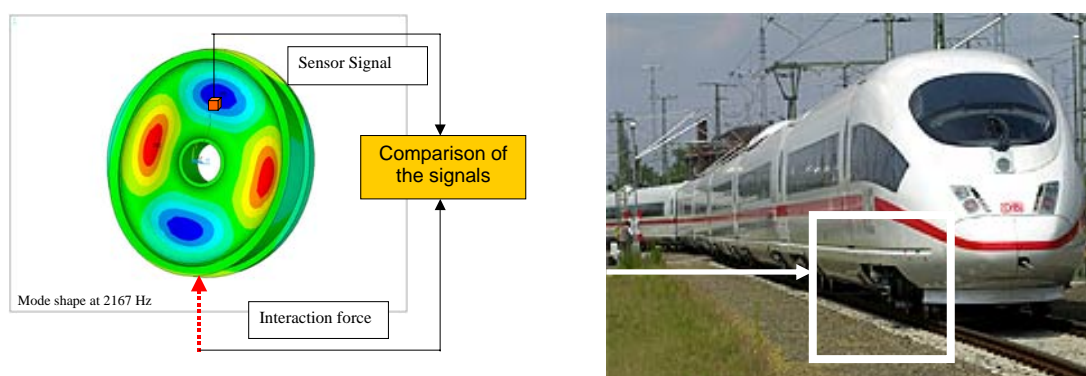


Fig. 5 The proposed method for the assessment of the roughness of the wheel. A piezoelectric sensor detects the vibrations of the wheel, leading to an assessment of its wear status (source: TU Darmstadt)

Energy Harvesting

Energy harvesting describes the process of changing parasitic mechanical energy, for instance of a vibrating structure, into electrical energy. This energy is used for other purposes, for example for driving an electrical circuit or for storage in a battery or a large capacitor. As generator materials, piezoelectric PZT devices (compare table 1) as well as polymers (PVDF) have been used in the past. Despite a relatively low efficiency factor of about 10%, the *absolute* amount of energy is sufficient for driving electrical circuits and a sensor electronics, what has recently been shown, Fig. 6. This makes it a candidate system for driving wireless sensors, especially in transportations. Especially in energy harvesting, the properties of the vibrating structure, the physics of the piezoelectric material and the electric circuit used for storage of the energy must be considered together instead of independent of each other. The reason is that the piezomaterial shows a degradation behaviour which depends strongly on the way how the electric circuit extracts the energy from the piezo, fig. 6. A holistic planning of the entire energy harvesting system is indispensable.

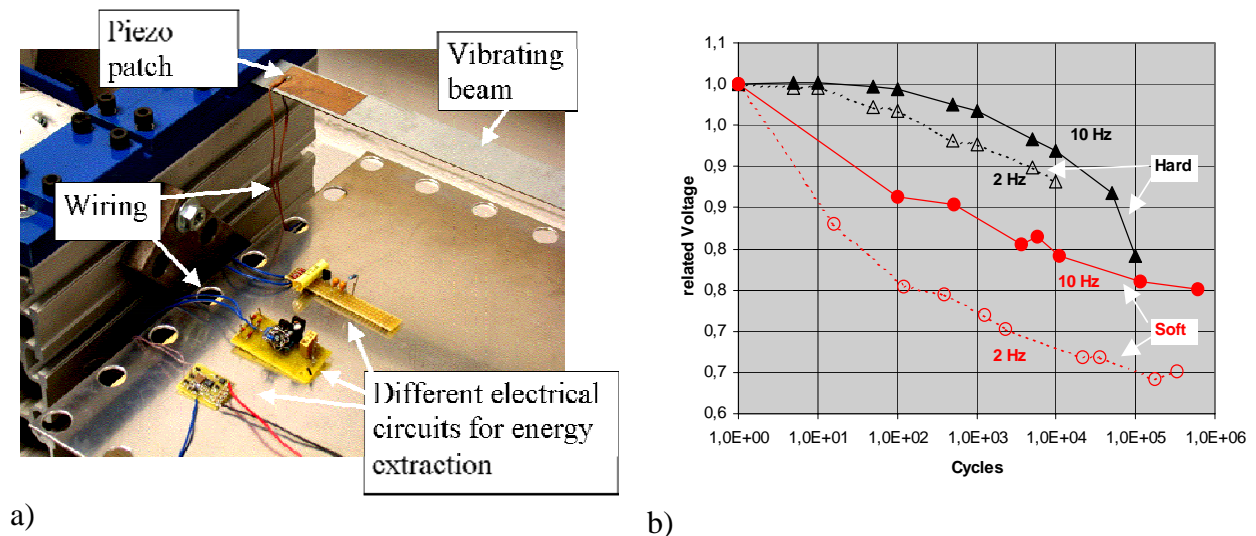


Fig. 6 a) Demonstrator for the principle of energy harvesting with 3 different electrical circuits for extracting the energy from the patch. b) Degradation behaviour of piezoelectric ceramic material of different composition (soft and hard) and different frequency of the mechanical excitation, resulting in a decrease of the output voltage. The results show that the combination of electric circuit and piezoceramic as well as mechanical excitation must be regarded as a system. (Source: LBF)

Reliability

Reliability in general is an important topic for all technical systems. A large amount of literature is available for classical methods in technical reliability [21].

Modern piezoelectric components like fibre composites are complex material systems which have not been investigated intensively in the past with respect to reliability.

Failure Mode and Effects Analysis (FMEA)

Since these material systems undergo a complex manufacturing process, not only typical material degradation failures, but also manufacturing and process – related failures must be considered. The Failure Mode and Effects Analysis (FMEA) is a well known method to identify potential failure modes already at early states of development.

For this purpose, an FMEA – like checklist has been developed recently at LBF, fig. 7. The goal is to separate physical failures from processing failures and to design the experimental phase as good as possible to the expected failure behaviour.

Based on the results of the modified FMEA, it is decided which kind of experimental test at which state of the product is necessary. Besides others, two main branches of experimental tests have turned out to be sensible.

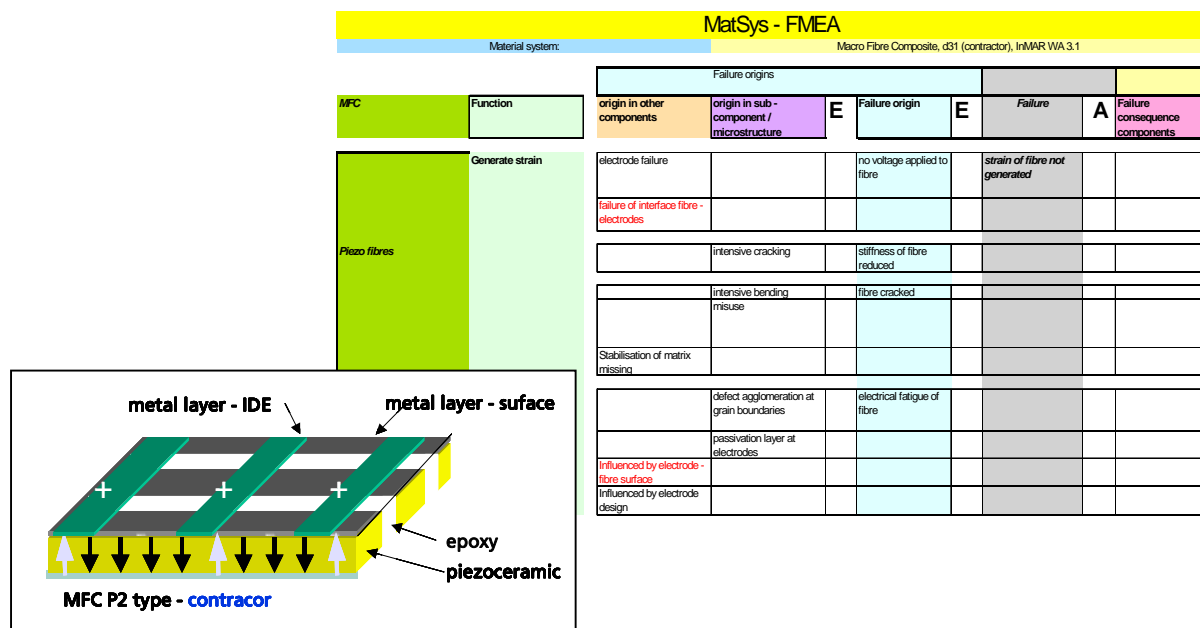


Fig. 7 Excerpt from a newly developed FMEA – like spreadsheet for the reliability assessment of complex material systems. The insert shows the inner structure of a commercially available piezoceramic fibre actuator (source: Smart Materials GmbH). The FMEA - spreadsheet allows for the introduction of multiple malfunctions and failure states as well as a systematic assembly of the failure modes with respect to their occurrence during the lifetime. Another new feature is that the interface between materials is treated like a system element. (Source: Fraunhofer LBF)

Lifetime Tests

This is the most often used type of test. It is sensible if a given failure mechanism is identified and the operational loads are known from previous investigations. Especially in case of active systems, however, this step is crucial due to the complex interactions of the system components influencing the operational load [22]. The probability of occurrence of these failures increases with increasing cycle number, and therefore the dependency of the failure probability can be described by an S-N-P – curve or, in case of multiple stresses – by an $(S_1 S_2 \dots S_i)$ – N-P area, Fig. 8. In the success run tests performed in the InMar project, a reduced number of specimens for a time t_{test} greater than the demanded lifetime were tested without any failure.

In case that the failure mechanism and its shape parameter of the corresponding weibull distribution is known, then a least guaranteed reliability $R_{i, min}$ can be given from the success run test theory [23]. In InMar, $n = 5$ samples were tested for twice the demanded lifetime L_{dem} (Lifetime ratio = 2) without any failure. In this case, as can be seen from fig. 8b), the least guaranteed reliability $R_{i, min}$ is greater than 90%. The material system is assumed to be highly resistant against degradation. For other failure mechanisms, however different test strategies must be applied additionally.

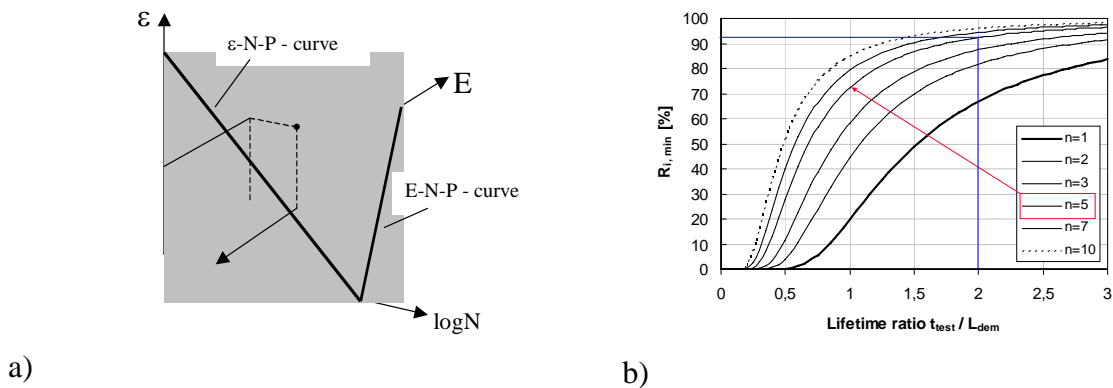
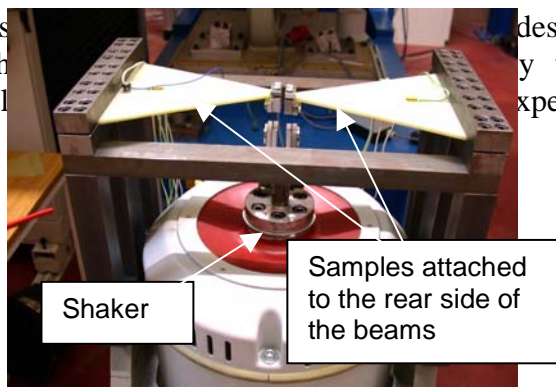


Fig. 8 a) For phase 3 – failures (material immanent degradation), the S-N-P concept of increasing failure probability is enhanced to a more – dimensional “failure – area”. In our case, especially the mechanical strain ϵ and the electric field E are the failure relevant stresses. The fatigue area schematically shows the cycle number until failure for given values of ϵ and E . b) Devices showing such a failure behaviour can be tested by the success run strategy. The diagram shows the dependency of the survival probability (reliability) on the number of test specimen and the related testing time. In our case, as indicated by the arrow, 5 samples were tested with a lifetime ratio of 2, leading to a survival probability $R_{i, \min}$ greater than 90%. (source: Fraunhofer LBF)

Highly Accelerated Lifetime Testing (HALT)

This high applied



design weaknesses of a system. The test strategy is to apply with much higher loads than expected in real expected [24].

Max. cycle frequency @ 0.3% strain	30 Hz	
temperature range	-40°C	+80°C
humidity	5%	90%

a) b)

Fig. 9 a) HALT test rig specially designed for cycling the piezoelectric test samples up to 0,3% mechanical strain. An electrodynamic shaker bends the vibrating beams, which are shaped such that the deflection along the whole surface is constant. This ensures that the attached samples experience a homogeneous strain treatment on their entire length. The choice of material for the beams is the most crucial part. The material must withstands all operational loads for high cycle numbers. On the other hand, its stiffness must be sufficiently high in order to introduce the strains into the samples without loss. The whole set-up can be integrated into a climatic chamber. The table shows the technical data of the HALT test set-up for piezoelectric modules (Source: Fraunhofer - LBF)

In case of piezoceramic patch systems this results in high demands to the test facility. These demands lead to the development of a new test rig, especially designed for testing of piezoelectric patch devices [25]. The details are shown in fig. 9.

In a work performed within a Fraunhofer – internal Project [26], the technique was applied to novel piezoelectric fibre sensors with integrated electronics, fig. 10. Before and after applying a cyclic strain of 0.2% p-p for 10^7 cycles at temperatures of -40°C and $+80^{\circ}\text{C}$, the ohmic resistance between several pins of the chip were measured. The measurements showed that none of the values increased to infinity after cycling, indicating that all chips and its contacting survived the procedure.

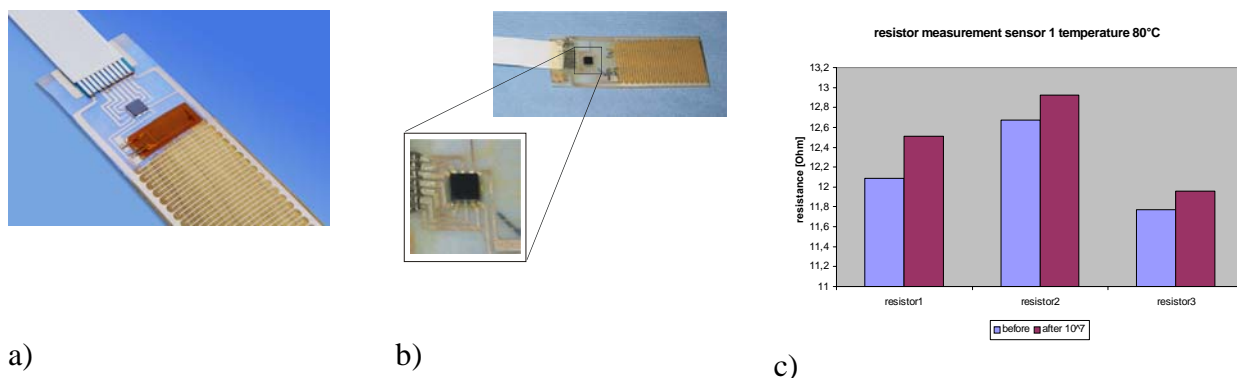


Fig. 10 a) Virgin piezoelectric sensor with integrated electronics (Source: Fraunhofer ISC). b) sensor after treatment with the HALT test setup. The small image shows the identified potential failure region at the pin connection [26] c) test of the electrical resistance before and after treatment showed no significant change, indicating that the contacts survived the extreme HALT treatment (Source: Fraunhofer LBF)

Acknowledgements

The partial financial support by the EU project “InMar” (funded by the EC, contract NMP2-CT-2003-501084) as well as by the Fraunhofer project “Mavo FASPAS” is greatly acknowledged. The authors are indebted to all project partners who have provided the material of their work; special thanks to: C. Nussmann, J. Nehl (FEV; “ANR of the oil pan”); P. Wierach (DLR; “High Temperature Piezocomposites”), A. Berkhoff (Uni Twente; “Miniaturized Electronics”), V. Carli (TU Darmstadt; “Wear detection of train wheels”), C. Klein, T. Koch (LBF; “Energy Harvesting”) B. Brunner (Fraunhofer ISC; providing the Sensors for “HALT Tests”)

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