Executive Summary:

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Objective

The HIPER-Act project has focused on materials research, the development of new piezoelectric materials, and electrode materials to be used for manufacturing actuators tailored for high reliability under extreme conditions and environments: humidity and high stress.

Technical results with commercial interest

- New piezo actuator with improved humidity and crack resistance based on new ceramic material composition and processing (this technology will be commercialised by NOLIAC)
- New stencils/paste have been designed and formulated for more narrow electrode printing of multilayer piezo actuators (this technology is made commercial by GEM and TECAN)
- New technology developed for wire electrode build-up of multilayer piezo actuators
- Actuators with new material and narrow electrode manufactured and tested in demonstrators
- Demonstrator of a new active trailing edge design is made and tested with successful results showing promising performance
- Demonstrator of a new bonding machine damping design shows very efficient passive and active vibration damping. B2 and IDE actuator showed less piezo performance however B2 actuator indicate better reliability than the reference material.
- Demonstrator of a new active engine mount design showed significant damping of vibrations
- Demonstrator and model of a new car control system (SCR AdBlue injection) design showed promising performance

Scientific results

- Increased crack/humidity knowledge (in design, manufacturing & performance) for piezo actuators

- Improved reliability model for piezo actuators
- Increased knowledge for ML design for improved resistance (e.g. FMEA)
- 47 technical reports, 8 periodic reports, 16 peer-viewed publications, 10 conferences/papers, 10 exhibitions, 4 identified exploitable foreground, 2 workshops and 1 patent application

Conclusion

During the HIPER-Act project novel ceramic material compositions has been developed and the production processes has been optimised and test have shown superior performance. Parallel have novel materials and methods for new internal electrodes been developed and optimised with result of significant reduced line width. Finally have piezo electric multilayer actuators, based on the novel developed ceramic materials and electrodes, been designed, manufactured and successful integrated and evaluated in 4 industrial applications.

The project was progressing according to plan (technical/budget) and this is due to high level of commitment and effort from all partners. The cooperation and communication between the partners was working very well and therefore the project was running smoothly and according to plan.

Project Context and Objectives:

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This 48-month LS-IP will be focused on materials research, the development of new piezoelectric materials, and electrode materials to be used for manufacturing actuators tailored for high reliability under extreme conditions and environments: humidity and high stress.

Piezoelectric actuators are used in an increasing number of applications due to their unlimited resolution, compactness, high efficiency, fast response time and high force capability compared to electro-magnetic actuators. A very successful application is the replacement of magnetic actuators for diesel fuel injection. For this application, piezoelectric actuators offer a 10 times shorter response time and much better combustion control, saving of fuel, reduction of emissions and more power. In the future it is anticipated that piezoelectric actuators will as well be applied for gasoline engines for all automotive engines, provided that reliability and cost requirements can be satisfied.

In more recent years, the multilayer technology has been developed enabling piezo materials to be used in actuators for active vibration control, for example in active engine mount. Also, car control systems have large potential, but innovations are limited by high reliability requirements and extreme working conditions, which are not met by today's actuator technology.

The wind turbine industry has focused on the development of blades with active trailing edge to reduce fatigue load and thereby substantially increase the lifetime of wind turbines and reduced energy price. The humid environment combined with extremely high reliability requirement provides a challenge for development of new piezoelectric materials for actuators. Successful progress in this field can be expected to lead to innovations in aeronautics including helicopter rotor blades and fixed wing aircrafts.

Wire bonding machines for manufacturing of semiconductors is another example of industries where active vibration control is expected to provide radical innovations in performance and quality. The challenge lies in extremely high load cycling numbers under high mechanical stresses and micro scale design of actuator systems.

Actuators for the various industrial applications require the piezo material to be operated at high electrical field, causing lifetime issues because of electro-chemical reactions and micro cracks in the brittle ceramic material. High humidity and high temperature further reduce lifetime of actuators. Significant research and development is still required to develop novel piezoelectric ceramic materials enabling higher reliability and the full utilization of the potential of the technology.

As further described in B3.2.2 (Annex I DoW) the potential benefits of using piezoelectric actuators in industrial application are very high:

- Lowering the cost of wind produced energy (conservative estimate by Vestas: 5%)
- Improving productivity and quality for wire bonding machines and enabling 3D-packaging of electronic equipment
- Fuel savings in cars (conservative estimate by Ricardo: 0,2 litre per 100 km)
- Creating new jobs in the European knowledge-based production sector.

As an example, the wind turbine industry expects that 1,250,000 large blades will be manufactured in 2020 to produce an expected 1250GW of power. Each of the blades would require 4 metres of the trailing edge to be covered by large piezo actuators, controlling vibrations in the blade. This application alone would require 5,000 tons of piezo material processed into actuators worth 1B. Another example is actuators for car control systems, where by 2020 an expected quantity of 1,4B actuators will be required for 140M vehicles (cars, busses and trucks). Combined with the expected 900M actuators required for diesel and gasoline injection systems, the estimated market for valve actuators will reach 6B� by 2020. The market for the new actuators to be developed in HIPER-Act is therefore expected to exceed 10B� and create 100.000 new jobs by 2020.

Two important aspects are currently limiting the full utilization of piezoelectric actuators, namely reliability and a costly manufacturing process. Reliability issues are mainly related to creation of micro cracks in the ceramic causing electrical short circuit and/or degradation of the electrical insulation of the ceramic material at high humidity level, also leading to electrical short circuit. The manufacturing process applied for piezoelectric actuators is basically the same as the ceramic multilayer process developed for ceramic multilayer capacitors in the 60�s. This process, while being ideal for chip capacitors with a thickness of less than 5mm, is however not ideal for making large piezo stacks up to 100mm in length. The reason is that, in order to make such large stacks it would be necessary to stack 1000 or more ceramic layers, each with printed electrodes. If one layer is incorrectly located then a whole block of material is wasted. Further, in order to dice actuators out of a 100mm thick block it is necessary to use rather thick dicing blades and long dicing time, significantly adding to the material waste and manufacturing cost.

It is important to improve piezoelectric multilayer actuators performance and reliability to meet the growing demand for such components from end-users with many different types of applications. The high production costs and problems related to obtaining reliable components explain that the utilization of piezo actuators up to now is far from having reached its full potential. The proposed research will lead to larger and more reliable actuators, capable of being operated at extreme operating conditions and at lower costs compared with the current technology.

Due to the reliability aspects, there is a need to develop improved piezoelectric materials, which can take higher loads before generating micro cracks, and which are not so much influenced by high humidity. Such improved materials are the first target of the proposed research. The second target is to reduce manufacturing cost. This second target will be achieved by an alternative manufacturing process for piezoelectric actuators; the Interdigitated Electrode approach (IDE). The IDE process builds up the ceramic layers in the horizontal plane as for the conventional multilayer process. The main difference is however the positioning of internal electrodes. For the conventional process the electrodes are produced in the horizontal plane as the ceramic layers and as the direction of actuation is perpendicular to the electrodes then a very high stack is required. However, for the IDE process the electrodes are located in the vertical plane and so actuation is perpendicular to the ceramic layers requiring only < 10mm thick blocks to be made. Such thin blocks are much easier to produce and dice and could lead to a 30-50% cost reduction for piezoelectric actuators.

Preliminary research at Noliac has shown that the composition of the ceramic material has a strong influence on the reliability at high humidity levels. Noliac engineers produced and tested multilayer actuators from standard piezoelectric materials from different vendors. Remarkably different reliability was achieved at high humidity, which can only be related to differences in composition. To date, it has however not been possible to identify why some material compositions are better than others the HIPER-Act project will clarify this and enable the specification and engineering of humidity resistant piezoelectric materials.

Tests performed at Noliac were done according to the IEC standard 68-2-67 with the following high humidity testing conditions:

- DC operation
- Field strength of 3kV/mm (usually 200V)
- Temperature 85ºC
- Humidity 85%RH
- Duration: 2000 hours

- Data logging of leakage current

A climate chamber was used and piezoelectric actuator samples were located in sample holders in the climate chamber. Examples of observed failure rate for 5 different ceramic compositions are shown in figure 1. A remarkable difference can be seen between e.g. soft1 and soft2 materials which clearly indicate that soft 2 has improved performance compared with soft 1. The test clearly indicates that there is a potential to engineer piezoelectric materials for high humidity resistance.

Another challenge is the requirement for larger actuators in particular for mass markets like pneumatic valves, fuel injection valves, pumps, vibration control systems, wind turbines etc. The current manufacturing technology for actuators strongly limits the size of actuators that can be made for reliable operation and reasonable cost. Larger, less costly and more reliable piezoelectric actuators would enable radical innovations in mass market for piezoelectric actuators replacing more bulky magnetic solutions.

Piezoelectric actuators are used for a large spectrum of applications where high precision and/or very rapid movements are needed. They are produced today via the well-known multi-layer technology originally developed for ceramic multilayer capacitors in the sixties. With multi-layer technology thin layers (20-200µm) of ceramic material are casted, whereupon electrically conductive electrodes are printed. A large number of layers and electrodes are laminated, whereby a laminate of desired thickness is produced. The laminates are subsequently sintered at 1000-1300°C, whereupon the components are diced in the laminate. External electrodes are applied on the single components and, to terminate the process, the components are polarized.

Applications for active vibration control in the automotive- and production industry, as well as control of blade geometry in the wind power industry, require the development of large size piezoelectric actuators, which can be produced efficiently at low cost with high manufacturing yield. The new components will provide a radical innovation for the involved industries and pave the way for new applications. The radical innovations will consist in an enhanced understanding of piezo material degradation and the development of piezo materials that have reduced density of micro cracks at severe operating conditions, as well as a new process methodology enabling large actuators to be produced at low cost. The new process requires the development of new electrode materials that can be used for creating very narrow electrode paths for internal electrodes in the actuators.

The HIPER-Act project will provide prototype components based on improved materials for four important applications representing large markets at the international level:

Industrial applications

Challenges

Expected impact

I: Wind turbines (active trailing edge).

- Potential applications in the aeronautic industry
- Harsh humid environment, high stress and extremely high reliability requirements.
- Higher efficiency of wind turbines and material savings. Reduced risk of fatigue fracture. Longer life-time.

II: Wire bonding machines.

- Potential application in several industrial production machines.
- Extremely high load cycling number, high stress conditions and micro scale design of actuators.
- Improved bond quality and reliability, higher productivity, more competitive, wider field of operation.

III: Active engine mount

- Potential applications in automotive industry for active vibration control.
- High stress and extremely high reliability requirements.
- Vibration reduction, better comfort, weight savings and reduction of fuel consumption.

IV: Car control system

- Potential applications in automotive industry.
- High temperature and extremely high reliability requirements.

- Improved reliability, weight savings and reduction of fuel consumption.

S&T objectives

The objectives of HIPER-Act can be grouped in

- Material research: Piezo materials and electrodes (objectives 1 and 2, WP2-WP6)
- Demonstration and test at four major industrial applications (objectives 3-5, WP7-WP12)

The majority of the resources are allocated on material research but test and demo are considered important because the selected industrial sectors I-IV represent major potential market for piezoelectric actuators. The industrial partners will

- Provide the specifications for actuator systems
- Play a central role, since they will ensure that the developed materials benefit to industrial applications and can be brought to commercial applications.

Project objectives

WP

Success criteria

1 Development of improved PZT based (Lead Zirconate Titanate) materials for extreme conditions.

- WP2, 3, 4
- Understanding the crack propagation mechanisms in piezo ceramics and the impact of humidity and stress. Development of piezo ceramics with high reliability at high stress and humid environment.

2 Development of new ultra-thin electrode materials

- WP5, 6
- Successful production of electrodes less than 50µm width.

3 Combining the new PZT materials and the new electrode materials in the production of multilayer actuators with interdigitated electrodes (IDE-actuators).

- WP7
- Successful production of IDE actuators which meet the industrial requirements on high reliability under high stress and humidity.

4 Test of components for industrial applications: Wind turbines, wire bonding machines, active engine mount and car control system.

- WP8, 9, 10, 11
- Successful test and demo of prototype components for industrial applications.

5 Dissemination and exploitation

- WP12

- Successful exploitation plans, training workshops and dissemination. Patents applications submitted.

Project Results:

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Ceramic Material Development

WP2 and WP3 were devoted to the development of new PZT material compositions with increased fracture toughness and robustness against humidity effects in order to fabricate piezoelectric devices capable to face high stress conditions and aggressive environments that are beyond reach with the present state of the art materials. The effective final achievements with multilayer actuators (MLA) based on the new materials overshoot substantially the initially estimated improvement of 50%. The best composition combined with the best material-device processing delivered improvements of up to 300% longer lifetime to failure compared to the original reference materials.

In the following we will describe and explain how these improvements were obtained.

First of all it is essential to provide the reader with a general view by depicting the Composition-Composite-Processing framework within which the best material solutions were sought. Figure 3.1 shows the framework within which the materials were selected, fabricated and tested.

The starting point is the central red cell labelled 5347 (Fig. 3.1), representing the standard industrial PZT composition Pb0.99Ba0.01 (Zr0.53Ti0.47)0.98Nb0.02O3 (5347 denotes the Zr/Ti ratio) used as reference during the entire project. The selected degrees of freedom around this standard to explore new solutions were the following:

A) the PZT composition (cells on the right and on the left of the red 5347) expected to influence the ferroelastic/ferroelectric domains, the microstructure, the piezoelectric hardness, the electric/piezoelectric properties and the general trends of the properties (understand) by large composition excursions (yellow cells)

B) the addition of zirconia particles with Y-stabilised tetragonal phase (red and orange cells below - different Y-content or particle size shown in 3D on the figure, white cells) or with monoclinic phase (blue cell above)

C) the processing conditions like milling, calcination, pre-treatments of the zirconia particles, sintering temperature, PbO excess/deficiency, and effects of additives (shown in 3D on the figure, white cells).

The 2 most important toughening mechanisms expected to be responsible for the aimed improvements were phase transformation toughening through a stress-driven phase transformation from the metastable tetragonal ZrO_2 phase into the stable monoclinic ZrO_2 phase and ferroelastic toughening due to switching of ferroelastic (non-180°) domains which can accommodate-reduce local high mechanical stresses by an optimal strain alignment (see Figure 3.1).

The positive impact of the PZT-grain size (which directly affects the ferroelastic toughening) and of the properties of the grain boundary phases was studied at first.

It can be clearly seen from the SEM micrographs the difference in grain size (5 vs 2?m) and in similar images (not shown here) the ratio lattice/boundary fracture. The toughening effect seen in these materials (Fig. 3.3) is due to the reorientation of domains. In materials with smaller grains, domain reorientation can be severely hindered by interactions with neighbouring grain boundaries, thereby limiting the ferroelastic toughening effect. Figure 3.4 shows that larger grain sizes promote the lattice fracture.

Ferroelastic toughening is expected to be directly proportional to remanent strain and indirectly proportional to coercive stress. At compositions close to the morphotropic phase boundary (MPB) its effect must be already maximal. On the other hand relaxation effects affect this mechanism when the external stress is reduced (the ferroelastic domains can relax back to the initial configuration). Figure 3.5 depicts the R-curves obtained for repetitive loading and unloading for a standard PZT and for a

PZT-Zirconia composite. The drop of crack toughness after each unloading is the result of the relaxation of the domain configuration. If the unloaded time is long enough to enable relaxation, the actual crack toughness is reduced back to its initial value and this represents a major limitation for this mechanisms. Interesting to remark that ferroelastic toughening is present in composites too and by the addition of zirconia the general toughness is substantially enhanced due to the transformation toughening effect.

The composites with $Pb_{0.99}Ba_{0.01}(Zr_{0.53}Ti_{0.47})_{0.98}Nb_{0.02}O_3$ as a matrix phase and different amount of tetragonal yttrium-stabilized zirconia (PZT 53/47-xTZ3Y, x=2, 5, 10 and 20 vol%) were prepared and analyzed (see red and orange cells in Figure 3.1). As anticipated, the addition of TZnY particles (n= % of Y content, 3 or 4%) is expected to drastically increase the toughness by providing a substantial stress release through particle volume increase due to the phase transformation "tetragonal to monoclinic", induced by the nearby passing crack and associated stress (Figure 3.6).

The highest initial crack toughness was measured in the composition PZT-10TZ3Y. However, this composition exhibited nearly no toughening behaviour and the deterioration of d33 was about 50% (Figure 3.7).

The highest crack toughness for crack lengths above 100µm was obtained with the composition denoted as PZT-5TZ3Y (Fig. 3.6). The deterioration of the piezoelectric properties was partially caused by the dilution effect and probably by a compositional shift of the PZT-matrix from MPB towards the Zr-rich rhombohedral phase due to the diffusion of Zr from zirconia particles into PZT. This shift could explain the suppression of ferroelastic toughening for PZT-10TZ3Y.

The most important undesired effects observed in the different PZT 53/47-xTZ3Y composites were the following:

1. Shift of overall phase composition towards a higher rhombohedral/tetragonal ratio
2. The small zirconia particles impede the desired grains growth of the matrix phase
3. Change of the electrical properties compared to those of pure PZT 53/47 ceramics
4. Presence of large clusters of particles and in homogeneity issues

All these issues were addressed on the selected most promising composite:

- Pb0.99Ba0.01(Zr0.53Ti0.47)0.98Nb0.02O3 with 5 vol. % of heterogeneous inclusions of tetragonal ZrO2 stabilized by 3 mol. % of Y2O3

In order to compensate the undesired compositional shift towards the Zr-rich rhombohedral phase, Ti-rich compositions of the initial PZT-matrix were used (5248 and 5149, see Fig. 3.1). The obtained improvements were not substantial and since the degradation of the piezoelectric properties was considered acceptable (<20%) it was decided to maintain as composite matrix the standard composition 5347. Concerning the inhibition of the grain growth of the matrix phase it was possible to demonstrate that if the initial zirconia particle size is large enough (monoclinic ZrO2 particles, see blue cell in Fig. 3.1) the grains of the PZT can reach the desired 3-5µm and the diffusion of Zr is drastically reduced. Unfortunately Y-stabilized tetragonal zirconia with larger grains is not available on the market. Attempts to increase their size by heat treatments were not successful. On the other side, an increased homogeneity and partial destruction of particle agglomerates could be achieved by adjusting the respective zeta-potentials (ZP) of the TZ3Y and PZT powders and the pH in the milling solution. By adsorbing the polyacrylic acid (PPA) on the surface of the PZT particles, the zeta-potential of PZT is changed (Fig. 3.8). At a pH = 5, the ZP of TZ3Y is +40 mV and the ZP of PZT+1wt%PAA is -40 mV. The ZrO2 is attracted to PZT resulting in a homogeneous mixture of both powders. The agglomerates of TZ3Y were further reduced by pre-milling and stabilizing the particles with adsorption of citric acid (PZT+TZ+1wt%CA).

Figure 3.9 shows a SEM micrograph of the PZT-TZ3Y composite prepared with the pH adjustment and TZ3Y-premilling with citric acid. The coalescence of the zirconia grains can still be observed, but the size of the agglomerates is substantially reduced. In Table 3.1 the density, dielectric and piezoelectric properties of PZT-TZ3Y composites with and w/o pH adjustments are reported. All samples were poled at 160°C under 3 kV/mm for 15 min.

The developed procedure was further refined by Noliac Ceramics with the following outcome: best results with shorter milling time, with highest sintering temperatures, little impact concerning the bead size and better properties with pH 5.

Industrial quantities of PZT-TZ3Y powders (2 times 50kg) were prepared (Noliac Ceramics) and used by Noliac Motion to fabricate MLA. The actuators were characterised under 30Hz dynamic loads (Fig. 3.10), with and w/o static preload at a renormalized stroke of 3.6µm and 3.8µm respectively (Figure 3.11 a and b). The time of failure was between 0 and 2 hours.

Figure 3.11 shows the distribution of times-to-failure (TTF) of the reference and composite based actuators for the 2 mentioned dynamic loads conditions. The actuators fabricated with the new materials and according to the new processing show up to 300% longer lifetime to failure compared to the original ones.

Figure 3.11 Statistical distribution of times-to-failure (TTF) of the reference and composite based actuators under 30Hz dynamic loads with static preload at a renormalized stroke of 3.6µm (a) and w/o static preload at a stroke of 3.8µm (b).

The humidity resistance of MLA based on the new materials have shown very good results with almost absence of detectable degradation. In both tested cases: (i) under identical voltage (resulting in lower strains for the new materials) and (ii) under identical strain (requiring higher voltages for the new materials) the newly designed composite materials exhibit superior humidity resistance in terms of failure rates and mean time to failure. Performances were tested in a standard Highly Accelerated Lifetime Test (HALT). The samples were exposed to extreme humidity conditions (T=85°C, RH=85 %, E=3 kV/mm) for ~12 days (t=288 hours) in a Weiss 160/40 climate chamber (Noliac Motion) or in an environmental chamber at EPFL at slightly different conditions (T=75°C, RH=75 %, E=1 kV/mm) for ~25 days (t=600 hours) by recording the leakage current. The stroke, capacitance and loss factor were characterized before and after the HALT test (excluding the samples with complete failure) and a general degradation of the stroke values for both, the reference and the new material actuators was observed.

To conclude, the MLA based on the newly designed composite materials overshoot too the initially estimated improvement of 50% in humidity resistance on account of about 20% deterioration of the functional properties.

Manufacturing of Ceramic Materials

Raw materials

The raw materials for the preparation of materials were chosen with attention about quality. The key raw materials ZrO_2, type AEZ-1M by Ashine Canada (purity 98,1%, d50 = 0,5mm) and Nb_2O_5 type Ceramic grade by H.C. Starck Germany (purity 99,9%, d50 = 0,59 mm) were used. The tetragonal stabilized zirconium with 3mol% Y_2O_3 TZ3Y by TOSOH Japan was used in accordance with the JSI recipe.

The basic PZT was prepared by mixed oxide technology using PbO (Penox, purity 99,8%), TiO_2 (Precheza AV-01 SF, purity 99,24%), ZrO_2 (ASHINE AEZ-1M, purity 98,1%), Nb_2O_5 (H. C. Starck, ceramic grade, purity 99,9%), $BaCO_3$. Purity depends on amount of humidity in material and other parameters.

Prepared batches

Technology 130 (batch 130) was reference batch for the project. From the composition of reference batch were derived 2 new technologies called technology 2 and 3. Composition for technology 2 and 3 was called composite material. Difference between batches 130, 2, and 3 was in second milling and mixing with ZrO_2 stabilized with 3mol% Y_2O_3 TZ3Y from TOSOH Japan. In batch 130 there is not any TOSOH zirconium oxide. In batch 2 was TOSOH zirconium oxide mixed with basic material on the start of second milling. In batch 3 was TOSOH zirconium oxide mixed with basic material at the end of second milling. These receipts were done according to recommendation from JSI in Ljubljana. All 3 batches were tested and samples were sent to universities joint in this program. According to test best performance of piezoelectric parameters are for batch 130. Best technology in testing of humidity resistance and mechanical properties was technology 2. Performance isn’t so big but humidity resistance and mechanical properties are better than for technology 130. All results from tests are in periodic reports prepared during the project. Best technology according to all tests for our purpose is technology 2.

Improving possibilities of technology 2

In technology 2 we are able to change a lot of parameters. Our aim is to increase performance of technology 2. For visibility of change we make only one change. All changes were done systematically. We could change chemical composition of whole material or change only content of minority elements. Next possible steps are in technology. We are able to change conditions of milling, temperature of sintering, polarization conditions etc. Some of mentioned changes were done.

One possible way how to improve performance is changing of composition. We tried change of Ti/Zr ratio and changing of Ba content. All tests in this branch show that the best performance is for current composite material of technology 2. In changing of Ba content was one better performance (3 % of Ba) but change wasn’t so big as we suppose. Ba decreases Curie temperature of ceramics. Each 1 % of Ba content decreases Curie temperature around 10 °C. And our aim is to have as high as possible Curie temperature. Curie temperature is important parameter of piezoceramic material. It shows us maximum work temperature of ceramics. When ceramics is heated over Curie temperature it loses its piezoelectric properties. All results shows that changing of composition isn’t good way and best performance is for current composite B2.

Next experiment was changing of milling conditions. Huge amount of samples was prepared. We tried milling in other time. Next part was milling with small milling beads. And third part was milling in other environments. All material was milled by 6 other times 4,5 min (0,15 kWh), 9 min (0,3 kWh), 13,5 min (0,45 kWh), 1 hour, 2 hour and 3 hours. Milling beads had dimensions 1,2 -1,4 mm. Rotates of mill during milling were 3600 per minute. Rotates of pump were 200 per minute. Our next experiment was milling with normal milling beads (from 1,2 ⍰ 1,4 mm) and small milling beads from (0,3 - 0,4 mm). And our last experiment in this part was milling in other environments. We tried environment of (water from water pipe, distilled water, water with dispergating agent and pH5). All experiments were done in small laboratory mill Netsch Labstar. Results from all 3 experiments are next:

- Milling in other lengths of time: the best performance was for the shortest milling. This time is equivalent (milling energy per 1 kg of material) with milling in big mill Netsch LMK4.
- Milling with small and big milling beads: this experiment gave us information that milling with small milling beads is much better for better shrinkage and smaller particles. But smaller particles in our case mean smaller performance. But this information is worthy for us.
- Milling in other environments: this experiment show that milling in water from water pipe is not as good as milling in water with pH5. Performance in all other 2

environments was not so big. But quite big increase of performance was in milling in pH5 environment.

Temperature dependence of performance

Measuring of temperature dependence is important property for characterization of material. It describes behaviour of performance in range of temperatures. Mainly we measured frequencies, impedance, capacitance and loose factor, piezoelectric current coefficient (d33). Measuring station was consisting from temperature chamber Brabender TTA32/70N, impedance analyzer HP 4194A and d33 analyzer YE2730A from Sinocera. Theoretical range of temperature chamber is from-70 °C to +100 °C. But practical range of chamber is only from -40 °C to +80 °C. Properties of samples were measured according to regulation about measuring of piezoelectric ceramics (EN 50324).

We have measured samples of best composite (B2) in temperature chamber in the whole practical range of chamber.

Repeating of results

Ability of repeating results is very important for mass production. Our prototype from technology 2 was marked as B2 (02/10). Copy of material from technology 2 was marked as B2 (01/11). Both batches were prepared by the same way. We tried possibility of our reproducibility. Samples from bath batches were send on analysis of XRF and RDA. All results were similar to each other.

Development of Narrow Electrodes by Screen Technology

The manufacturing process applied for piezoelectric actuators is basically the same as the ceramic multilayer process developed for ceramic multilayer capacitors in the 60's. This process, while being ideal for chip capacitors with a thickness of less than 5mm, is however not ideal for making large piezo stacks up to 100mm in length.

The IDE process builds up the ceramic layers in the horizontal plane as for the conventional multilayer process. The main difference is however the positioning of internal electrodes. For the conventional process the electrodes are produced in the horizontal plane as the ceramic layers and as the direction of actuation is perpendicular to the electrodes then a very high stack is required. However, for the IDE process the electrodes are located in the vertical plane and so actuation is perpendicular to the ceramic layers requiring only < 10mm thick blocks to be made.

Such thin blocks are much easier to produce and dice and could lead to a 30-50% cost reduction for piezoelectric actuators.

In order to apply the IDE concept for piezoelectric multilayer actuators, it will be necessary to significantly reduce the width of electrode paths. To obtain actuators operated at 200-300 V it is required that the distance between the electrodes is 100 m or less, which requires an electrode width on the order of 20 m or less to achieve a high performance.

Current technology based on screen printing will allow 75 m electrode lines and spaces, prototype prints can achieve 75 m lines and spaces, while fine laboratory prints can go down to 50 m lines and spaces. This is achieved by using meshes with greater thread counts per inch/cm

There are limitations with using screens in order to achieve fine lines and this is related to the fact that mesh is used to used to manufacture conventional screens. For screen meshes with high thread counts the amount of open area within the mesh which allows ink to flow through to the substrate being printed on to is significantly reduced, and can lead to reduced deposits. Maintaining print definition is difficult due to the fact that the ink must have a degree of flow, however this rheological property of the inks, also means that definition is lost and printed line widths increase.

It was an objective of the research to provide a technology and electrode materials for producing very thin lines of the order of 20 ?m in multilayer ceramic actuators. New electrode ink formulations for fine line stencil printing had to be developed involving work with much denser metal powders and advanced polymer technology to produce fine line definition interdigitated structures, as well as looking at alternatives to conventional screen technology, to print these inks and eliminate the normal print faults that would be seen.

The alternative to using a conventional mesh screen is a stencil. The stencils were electroformed, so there were no obstructions within the print area to limit ink flowing drying the printing process. These were used for the initial trials, and found to give exceptional results, however they were fragile. In order to improve this, a support structure was electroplated in the aperture of the stencil to give a mesh like structure in the open areas of the stencil. This added a degree of robustness to the stencil which enabled the use of such stencils in a production environment. However due to his mesh structure being electroplated, the width is significantly smaller than would be found with a conventional mesh screen being in the order of ~5 -10µm.

The second photomicrograph shows a platinum paste print using this mesh, with no breaks in the IDE�s, showing good definition and continuity.

The third photomicrograph shows a cross section of a test actuator, in cross section, showing the positioning of the electrodes within the ceramic body following firing. In these test pieces there were alignment issues which were later resolved.

Development of Narrow Electrodes by Wire Technology

The aim of work package 6 has been to develop the technology required for realizing an actuator based on the IDE design by using embedded solid metal electrodes.

The first task was to specify the requirements for the electrode performance and the geometry which would yield the best performance. Based on these specifications it was found that the initial concept for placing the solid metal electrodes using a wire bonding machine was not feasible. The total length of the electrodes required for building one actuator was too large, and a wire bonding machine would wear out after producing a couple of hundreds finished IDE actuators. Following an analysis of the requirements, the project partner IDS took over the task of developing a custom wire positioning equipment from H&K.

Based on the requirements for the electrode material and the geometry a thorough study was carried out by IPU on what materials could be used and what method should be used to manufacture the electrodes. Since the electrodes would be applied to the green PZT material as a solid and not as a paste, a concept was to build up the solid electrode with different layers to reduce use of the very expensive standard electrode materials (platinum and palladium) and the associated manufacturing cost. A study was carried on different methods for manufacturing the electrodes with the desired size (25µm) and 14 different possible manufacturing paths was analyzed and described. 6 of those are shown on figure 3.18.

A critical review of the different manufacturing paths lead to the conclusion that only wire drawing would yield wires of the required diameter at a cost which would be realistic for mass production in the lengths (several 1000m) required for a large IDE actuator. A rig was build allowing for batch coating of wires in unbroken lengths of 20m and this setup was used to test more 19 different combi-nations of wire materials and coatings, the cross section of some of which are shown on figure 3.19.

After an initial run in phase it was possible to batch coat 20m of wire with a good result, for any combination of layers of copper, silver, palladium and platinum, using tungsten or nickel as base material.

19 different combinations of basematerials and coatings was manufactured and sintered embedded in PZT material at 1300°C in an oxygen rich atmosphere. Of these only tests with electrodes made from pure platinum and palladium showed no visible degradation of the PZT, and even the pure palladium electrode showed a led content of 15% in the center of the electrode, corresponding to the solubility of lead in palladium at 1300°C. One of the initial problems are shown in figure 3.20, where stress induced cracking in a platinum coating is clearly seen, these challenges were ovecome and the final optimized coating with no defects is also shown on figure 3.20 (centre). A post sintering SEM image of a tungsten electrode coated with silver and platinum is shown on figure 3.20 (right), where it clearly shows the tungsten has migrated into the PZT material, leaving only the coating layers in place.

The conclusion on the work on the electrode material and processing was the only pure platinum was unaffected by the sintering process. To avoid delays in the project it was decided to use pure platinum wire for the future work with the buildup of the IDE actuator, to avoid any potential negative influences by palladium.

Following the changes in the original project plan, IDS were responsible for designing the equipment required for positioning the electrodes on the green PZT substrate. Based on the experiences from the setup used for batch coating of test electrodes, it was decided to use a concept in which the wires were mounted on 100mmx100mm frames and the frames were then stacked together with the green PZT substrates to make the final IDE actuator. An innovative concept was developed on which four frames were mounted on a spinning cube and then electrode wires were wound onto this cube using controlled pre-tensioning. The wires were mounted with a pitch of 180µm resulting in the mounting of 550 wires on one 100 mm wide frame. A schematic of the winding concept is shown on figure 3.21 together with a close up of the thread machined on the sides of the cube, to ensure correct poisoning of the wires.

The competed electrode wire mounting device is shown on figure 6, together with a selection of finished frames and a close up of the wires mounted on one of the frames.

The final part of the workpackage involved manufacturing the PZT actuator itself. The first process was stacking the frames with the electrode wires together with layers of green PZT substrate and compressing the final sandwich to remove any voids. This was followed by a trimming operation in which the frames were removed, leaving the metal electrodes embedded in a PZT matrix in the correct locations. A normal PZT sinteringprocess were then carried out followed by a glass deposition process, in which the end of every second electrode wire was insulated. Electrical connection was created by applying silver paste to the non insulated ends. After dividing the sample into two identical parts, the electrical connections could be finished, yielding two IDE actuators for each assembly process.

For the build-up of IDE actuators utilizing solid wires as internal electrodes a novel manufacture method has been developed.

Despite of the wire electrode approach being a wild card solution the Hiperact project has proven that it is possible to manufacture an IDE actuator based on solid metal wires.

Development of Actuators

Throughout the project, WP7 has addressed the reliability on several different levels ranging from material benchmarking tests on a laboratory level, over end user tests on sub assembly level to failure analysis on an entire piezo pump system.

As the laboratory tests serves to map the reliability and performance over time in several predetermined conditions the end user tests will address the achieved reliability under conditions similar to actual use.

Laboratory tests, performed on standard multi layer (ML) actuators, revealed during material development phase that the composite developed 20% less strain than the reference material under identical applied fields. From literature an increase in strain has been proven to be linked to a decrease in mean time to failure (MTTF).

To exclude the strain difference as reason for any difference observed in humidity resistance, a series of tests under extreme conditions (85% relative humidity/85oC) were conducted under different applied stresses.

In the figure 3.24, each point represents the average MTTF of a sample batch of at least 20 MLA’s at a given strain. Readily observable is the fact that even when the reference samples are developing less strain than the composite counter parts the mean time to failure of the reference samples is not exceeding the MTTF for the composites (circled in red). This test cannot exclude the risk of strain enhanced failure, but from this test it can be concluded that at identical strain the composite material show a higher tolerance towards the extreme environment, than the reference material.

Further thorough testing performed on MLA samples also revealed the same strong potential benefit of the developed composite material as shown above.

In summary of the conducted tests, the improvements on lifetime and hence reliabilities under the tested extreme conditions compared to reference samples are found to be:

From long term fatigue testing in ambient conditions it was found that the changes in performance of the composites were very similar to the changes seen for the reference material, which also is an important result in the pursuit of launching the composite material as an high humidity alternative.

Sub-system tests

For comparison of the reliability on sub-system level wire bonding tools from WP9 were mounted with reference and composite samples respectively. Below, in Figure 3.25, is a picture of a wire bonding head with vibration cancelling actuators mounted.

Under normal operation conditions no change in performance was seen for either of the tested samples. To reduce the test time the temperature and humidity were gradually increased. After 1011 cycles one of the reference samples failed which can be seen in the top plot of Figure 3.26, whereas the composite samples are unaffected by the conditions as seen in the lower plot of Figure 3.26.

Due to the small quantity of tested samples it cannot be fully concluded that the composite is better in terms of reliability, but the results are in thread with the findings on laboratory level.

Early generation IDE samples were also tested, but due to the early stage of development these samples did not perform to their full potential. Improved IDE actuators with increased functionality have been manufactured, but are yet to be tested.

In depth knowledge about the entire system and component interactions is key to a successful development of a fully functional and reliable product. Using a Failure Modes and Effects Analysis (FMEA) gives detailed insight to strengths but especially weaknesses of a system. Obtaining the necessary level of information is labor intensive and time consuming, but can quickly be worth the efforts.

Partners from Fraunhofer LBF and WP11 used such a FMEA tool on the entire piezo pump system developed in WP11. From the analysis a few focus areas were identified as:

- Positioning and preloading of the piezo stack
- Reliability of piezo actuator
- Thermal properties of the involved materials and self heating of the piezo actuator during operation
- Corrosion resistance of the involved parts as the liquid to be pumped is very aggressive

From the developed prototype the functionality can be readily assessed, but knowing the entities listed above will significantly ease the process of maturing the product for the market application.

Industrial applications I: Wind Turbines - Active trailing edge

Introduction

The chapter describes the work carried out in Work Package 8A and 8B concerning industrial application of the piezo electric actuators in active trailing edge flaps for wind turbines. In the Work Package a trailing edge flap dedicated for wind turbine blades has been designed and tested. Originally it was the intention to use piezo electric benders like the Thunder TH-6R from Face International, where the intention was to attach them directly to an airfoil trailing edge and test them in a wind tunnel. The requirements to such actuators were described in the deliverable from WP8A1, where the objective was to provide specifications for the IDE actuators for active trailing edge. However, it turned out that the bender-type of actuator could not deliver the needed forces, so an actuator designed for application on helicopters was used instead. Since the operational principle of a trailing edge flap using this type of actuator is fundamentally different form the piezo electric benders, an additional task in Work Package 8 was to design a mechanism, which could transfer the movement from the alternative actuator with significantly bigger forces and small deflections to a rigid flap attached to the trailing edge of an airfoil. During the summer and autumn 2011 the mechanism was designed and it turned out that at least three actuators were needed to drive the flap mechanism on an airfoil mounted in the LM Wind Power wind tunnel, where there were advance commitments for wind tunnel tests. End February/start March 2012 the actuators were delivered from Noliac to DTU Wind Energy. At that time DTU Wind Energy tried to make a reservation for tests in the LM Wind Power wind tunnel, but it was not possible to find testing possibilities before September 1 2012, where the project ended. Investigating the possibilities in other tunnels, such as Stuttgart Laminar Wind

Kanal, Germany and the Delft Low-Speed Low-Turbulence wind tunnel, Holland, there were no possibilities for tests at such short notice. Therefore, it was decided to build the flap mechanism anyway, but test it in the laboratory with the forces on the flap using springs instead of aerodynamic forces. Thus, the deliverables in Work Package 8A.2 and 8B.1 were changed from creating a prototype airfoil section with active trailing edge and carrying out a full scale performance test of airfoil in wind tunnel, respectively, to design of a trailing edge flap actuation system using the delivered actuators, design of a suitable test setup to emulate the key features of the aerodynamic forces and test of the new setup.

Design and construction of the flap mechanism

Based on the actuator delivered by Noliac and the corresponding forces and deflections a flap mechanism was designed. It was decided to carry out a simple design because of a requirement for wind turbines of high reliability. The dimensions of the flap originate from the original planning which included wind tunnel tests. According to that, the length of the flap should be 1350 mm, the chord 90 mm, and there should be three actuators placed along the length. Therefore the test flap was designed as shown in Figure 3.273.27 left, but with a length of 450 mm and only one actuator. Based on this design the flap was constructed as shown in Figure 3.27 right. The constructed flap was tested and the flap mechanism was functioning as expected with low losses. In both downwards and upwards direction the performance is rather good according to the predictions, however, with only a deflection of between 0.95deg and 1.3deg. Relating to the specifications established in WP8A at least +/-10mm deflection is needed. This corresponds to +/-6°. According to the design considerations, this could be obtained by selecting another gearing in the flap mechanism or more power from the piezo ceramic elements, or both.

Simulated performance of the flap mechanism on a wind turbine

Simulations of trailing edge flap with maximum deflections of 1° and 5° and blade pitch of 1° showed that the stated 6° in the specifications of the actuator is a minimum. However, it also showed that if such a deflection could be obtained, significant reductions in the standard deviations of the loads could be obtained.

Conclusions

A demonstrator of a flap mechanism based on piezo ceramic materials was designed, tested and evaluated. Based on the measurements in the laboratory it was concluded that the flap mechanism was functioning as expected with low losses. In both downwards and upwards direction the performance is rather good according to the predictions. The design considerations showed that the deflection of the unloaded flap needs to be significantly larger than the maximum deflection needed in loaded conditions. As stated in the specifications for the design of the flap mechanism at least +/-6° was needed. According to the measurements this was not obtained, but the extra deflection could be obtained by changing gearing in the flap mechanism and/or using more piezo ceramic elements per spanlength of the blade. Concerning the future work within this flap mechanism it is needed to mature the technology and the following list include some of the issues and challenges that could be considered:

- The flap mechanism should be very simple overcoming in the order of 3 billion cycles
- The flap mechanism including the piezo ceramic elements should be proven to withstand humidity and lightning
- The flap mechanism needs high power, with a corresponding increase in weight. Thus, the weight of the flap mechanism should be low
- The total cost of the flap mechanism should be relatively low

Industrial applications II: Wire Bonding Machine - RTD

Introduction

Ultrasonic wire bonding is an established technology to connect the electrodes of microelectronic devices as well as power electronic modules. Typically an aluminium wire connects the electrodes of a microchip or a power semiconductor with the corresponding electrodes of a substrate. The bonding of the wire to the electrode surface is made by an ultrasonic friction welding process. The very high requirements concerning the quality und the reliability of the electric connections ask for very good control of the process. Additionally increasing miniaturisation and machine speed ask for even better control of the bonding process. Another challenge is bonding on crucial surfaces, like on pads with soft underlayer, slim pins or overhanging stacked chips.

Objective

The ultrasonic transducer is a key component of a wire bonding machine. It generates the ultrasonic vibrations for the bonding process and is driven in a longitudinal vibration mode. In general, all vibrations not in line with the main direction of the ultrasonic bonding process are not desired and can disturb the process. Therefore at the beginning of the project extensive vibration analysis have been conducted by spatial laser interferometer and accelerometer measurements on different points of the machine. It turned out, that the initially addressed low frequency structural vibrations induced by the machine dynamics during operation movement are not as critical as the ultrasonic vibrations caused by eigenfrequencies of the so called ultrasonic transducer. This is because of the special soft design of the suspension of the transducer unit, effectively decoupling the vibrations from machine side. Generally, beside the main longitudinal eigenmode additional parasitic vibration modes exist. These eigenmodes, e.g. bending modes of the transducer, as well as not perfectly symmetric longitudinal modes can lead to fluctuating normal forces in the friction contact and a disturbance of the bonding process. Therefore the objective was slightly adapted to focus on the ultrasonic vibration damping, without major effects to the work and cost plan.

The aim of this project is to suppress or at least reduce these unwanted vibrations during operation by the use of special control actuators and a proper vibration control strategy.

Approach

A novel prototype transducer is developed, which is capable of suppressing these unwanted vibrations using additional piezoelectric actuators (see Fig. 3.29 left). It is desired not to influence the main longitudinal vibrations, but only acting on the orthogonal vibrations. This is achieved by applying two additional piezoelectric control actuators on top and bottom side of the transducer body. The polarisation of the top control actuator is chosen in such a way that in free ideal longitudinal vibration mode the electrical charges on the electrodes of the top and the bottom control actuator cancel out each other and the control actuators act neutral. In contrary applying a voltage to these actuators induce a pure bending or vertical movement, respectively. So an optimal coupling is achieved for the parasitic bending mode.

Deriving Specification for control actuators

Within the first part of the work programme of this project two tasks have to be performed. The detailed specification for the control actuators has to be determined and a proof of concept demonstrator has to be built. The proof of concept demonstrator includes the evaluation of different vibration damping techniques passive and active.

To fulfil these requirements a suitable model is essential for evaluation. Therefore the ultrasonic transducer has been described by a Finite-Element model, which can be used to calculate the dynamic vibration behaviour of the transducer. By aid of this model amongst other issues the optimal placement of the additional piezoelectric actuators have been determined. The FE-model has been validated by frequency response measurements with different contact conditions of the wedge. In particular, the friction contact between the wedge tip and the bond pad has been modelled. Additionally a modal reduction of the Finite Element model to the two most relevant eigenmodes. The system is then described by two degrees of freedom (2 DOF model), which can describe longitudinal and bending motions. This model is essential to design the active vibration control.

Proof of concept demonstrator for active vibration control

The proof of concept demonstrator transducer has been built according to the Finite Element Model with optimal placement of the control actuators. Because the newly developed HiPer IDE actuators have not been available at this stage of the project, the first prototypes were built with conventional piezoceramics. Once the design study has been finished, a prototype transducer has been set up with a first IDE sample, see Fig. 3.29.

Different vibration control techniques are studied in this project. A piezoelectric shunt damping technique and an active open-loop control. For the first case, a passive inductance-resistance (LR)-circuit is connected to the electrodes of the piezoceramics, in simulations as well as on the prototype. This passive damping technique doesn't require external power and is guaranteed stable. For proper operation the network parameters must be tuned precisely. Measurements of the free vibrations and the frequency response showed an increase in damping of the parasitic vibration modes of more than 10 times. However, a total suppression is not possible with this technique. Further on, an active open-loop control has been set up. The required voltage amplification and phase shift compared to the driving actuators, which cancel out vertical vibrations at the wedge tip, have been calculated using the reduced 2 DOF model of the transducer, and again validated by measurements. In experiments, the active control was capable to totally suppress the parasitic vibrations. Further studies with pure friction contact at the tool tip show that the active control again can reduce the basic harmonic completely, but higher harmonic vibration content of quite low amplitude remain. Results prove that for both techniques the piezoelectric coupling is the most important parameter for the mechanical design. Especially the new IDE piezo type is capable to increase this coupling because of the special electrode design.

Within the project, the standard piezo-actuators have been replaced by an actuator from new NCE 51 B2-2 bulk material as well as a first sample of an IDE actuator. The same measurements have been performed and their performance is compared to the standard actuator. The measurements showed that the new HiperAct material causes only a slightly lower coupling factor. The working ability of the new IDE actuator was successfully shown; however the coupling factor of the first prototype was much lower than calculated due to not fully functional inner electrodes of the first prototype. A future series actuator with full performance will show much higher coupling.

Full scale performance test

In the second part of the project a full scale performance tests was to be done. Therefore a bonding machine was equipped with a two channel ultrasonic driving system and two power amplifiers as well as a special software to control both channels. The full scale performance test proved that the proposed shunt damping technique and the active vibration control are capable to improve the vibration behavior during bonding significantly, especially in difficult circumstances e.g. on soft bonding surfaces. Many bonding tests have been conducted and all relevant signals have been measured. It was found that both techniques do reduce the unwanted vertical vibrations significantly, if tuned correctly. A further promising observation was a reduction in the natural fluctuations of the horizontal vibrations during bonding. This means the standard deviation of the measured signals was decreased.

The passive shunt damping technique with a tuned LR-network shows a significant damping effect of about 50% reduction, but frequency bandwidth is quite small. So the correct inductance value must be met quite accurate. Possible frequency changes during operation due to temperature and power depending drifts have to be considered. The advantages of the passive shunt damping technique are the simplicity and guaranteed stability. No additional hard- or software is necessary. But the lower damping performance and the sensitivity towards parameter deviations are limiting its application.

The very profound advantage of the active feedforward vibration control strategy is the possibility to realize an almost complete suppression of orthogonal vibrations at any desired operating frequency. But for this considerably more control effort and supplying high electrical voltages to the control actuators is necessary. It was found that because of the non-linear time-varying bonding process the optimal control settings change over time. Therefore a vertical vibration sensor supported closed loop control is a promising future project.

Concluding the passive vibration damping system can be incorporated with low effort into a serial machine. For application willing to spend more effort in the vibration damping system to reach optimal performance even the active vibration control is reasonable to implement in future machines.

Industrial applications III: Active Engine Mount - RTD

Final performance analysis of the active engine mount with different error sensors (acceleration at chassis side of the engine mount and sound pressure at drivers head position) were taken in the Adaptive Structures Test Facility (ASF) at the Fraunhofer Institute LBF. The vehicle is mounted on a stationary rig; the driven wheels each attached to a speed controlled asynchronous motor. The measurement schedule consists of acceleration and sound pressure measurements during run-ups from 1000 to 4500 rpm under different throttle settings in second gear (10 -50%). The engine speed was set using the asynchronous motors, thereby determining the engine load during the run-up. For comparison, measurements were taken for the serial mount, for the uncontrolled active mount and the controlled active mount as well. Accelerations were measured at the chassis side of the engine mount; the sound pressure was measured in the passenger cabin at head position. The acceleration and sound pressure signals were sampled at 2048 Hz and collected by an LMS data acquisition system.

Several speed-controlled run-ups were performed within 60 seconds from 1500 to 4200 rpm and an accelerator pedal position of 30% of maximum to optimize convergence behavior of the controller. During these measurements the adaptive controller reduces the accelerations at the mounting points by means of the previously introduced control concept.

Figure 3.30 shows final results for the acceleration at the mounting point during a complete run-up for the serial mount, the uncontrolled active engine mount and the controlled active engine mount (whereas the controller uses the mounting point accelerations to adapt its weights). A significant reduction of the acceleration amplitude up to 25dB can be observed between the uncontrolled and controlled active engine mount. Compared to the serial engine mount, amplitude reductions of 20dB can be observed. Furthermore, the second order sound pressure level at the driver's ear is also positively influenced by the active engine mount, even though the controller does not yet take the measured sound pressure into account in this analysis.

The final results of the next setup are shown in Figure 3.31. Here the second order sound pressure at drivers ear during a complete run-up for the serial mount, the uncontrolled active engine mount and the controlled active engine mount (whereas the controller uses the sound pressure at driver�s ear to adapt its weights) is depicted. A significant reduction of the sound pressure amplitude up to 20dB can be observed between the uncontrolled and controlled active engine mount. Compared to the serial engine mount, amplitude reductions also of 20dB can be observed. The sound pressure reduction is slightly more efficient in some rpm regions compared to the previous setup.

However, in this case the second order mounting point acceleration is increased in some rpm regions. This can be explained because only one transfer path is controlled. The controller optimizes its weights in order to cancel the error sensor signal completely. Therefore the controller try to compensate all other transfer path's with (one) active engine mount. To realize that objective obviously higher accelerations at the engine mount position are necessary.

To further improve the active engine mount behavior an optimized design (see Figure 3.32) for the stroke amplification mechanism of the piezo actuator is developed. The new one produces the same stroke as the previous design, but the maximum stress is reduced significantly (approx. 15 %) and simultaneously the resonance frequency is slightly (approx. 5%) enhanced. By realizing this concept a more robust and reliable mechanism is expected.

Industrial applications IV: Car Control System RTD

WP 11 aimed to develop a concept for a reciprocating pump actuated by a Piezo-stack, based to be of the new type resulting from the overall HIPER-Act project. This pump was intended to be applicable to Car-Control-Systems. A thorough screening of achievable features and data for the pump on one hand and potential benefit led to the decision to demonstrate high pressure (50 bar) injection of AdBlue® (Urea Solution) into the exhaust system for SCR (Selective Catalytic Reduction) NOx aftertreatment.

The advantages of piezo actuation are of special importance in this application: high pressure enables good spray preparation and the inherent options for fine control of stroke and frequency will allow a new level of precision in metering the dosing of an important reactand for the catalytic reduction. The possibilty to shape the lift (and thus the injection rate) at individual injection events enhances performance at (relatively) low frequencies and contributes to the fine adaption of injectiuon to the exhaust gas flow, so avoiding many issues with crystallisation of urea.

Since the lift of piezo stacks is very low, the necessary flow rates can only be reached by employing high frequencies.

After detailed simulations a new design for the pump was developed. A special Belleville-type spring was designed and integrated in Simhydraulics model in order to maintain stack preload, control piston postiioning and effect the sealing.

At 600 Hz maximum flow rate of 270 cm3/min at the pump test bench was achieved.

Design of the pump

As the pump needs to operate at high frequencies, the eigenfrequency of the pump valves must be very high. This is one of the main challenges. To get such a high eigenfrequency the moving mass of the pump valve and its spring had to be minimized. After comparing different valve designs, poppet valves were chosen (Fig. 3.33). The valves are closed by a coil spring. To get minimal mass the thickness of the valve head was fixed at 0.3 mm for a pressure load of 50 bar. This was confirmed by FEM analysis. With a steel valve a mass of 0.1 g was achieved. Additionally 1/3 of spring mass has to be taken into account. In order to have a reliable system only one low and one high pressure valve is used.

To avoid leakage through the annular gap cause by the piston clearance a new kind of clamped Belleville-spring sealing is used (Fig. 3.33), which is only feasible with the small strokes of a piezo stack.

Within the timeframe of the project the main focus of Ricardo was to make maximum use of simulation. The basic simulation for the hydraulic system was done by using MATLAB/Sim-Hydraulics. A parametric model of the piezoelectric actuator was developed by Fraunhofer LBF. The equation of motion for the valves was programmed by Ricardo. With this tool the function of the system could be assessed and dimensioning was achieved quickly. The basic simulation assumed a stack with a blocking force of 6000 N and a maximum stroke in unloaded condition of 60 µm.

Testing results with completed proto type system

The completed prototype system was tested on a hydraulic test bench. As simulation had shown, the timing of the valve lift is very important for the flow rate especially at frequencies above 200 Hz. For this reason very small inductive lift sensors were developed, which allowed to measure valve motions. Additionally pressure in the compression chamber and the piston lift were measured. There was a good correlation between simulation and measurements.

A new power electronics especially for the piezo pump application was developed by Ricardo. The Ricardo power electronic was tested in the complete system (Pump and outwards opening DI-Injector) with the B2-HIPER Act stack. The flow vs frequency diagram (Figure 3.34) shows that up to 300 Hz the flow with the Ricardo Power electronics gives a much better result as with the standard electronics.. The change in the gradient of the flow at 300 Hz is due to damage of an electrical component in the power electronics, which resulted in a reduced maximum voltage at frequencies above 300 Hz.

The target flow of 150 cm^3/min for the truck is achieved at a mere 220 Hz. The flow rate for passenger cars of 25 cm^3/min can be reached with a much smaller pump.

Potential Impact:

#PLEASE READ ATTACHMENT FOR BETTER LAYOUT#

Noliac A/S

Noliac plan to protect the new inventions related to piezoelectric actuators and materials. Some protections may be jointly owned with other partners in the consortium or Noliac may license the IP from other partners. Noliac has our own IPR engineer and the new material, process and products are evaluated for potential patent.

Noliac plan to fully commercialise the developed technology through our worldwide sales network, subsidiaries and distributors. The new more reliable materials are in progress of being directly implemented in Noliac existing multilayer actuator production and will be efficiently marketed as a new generation of more reliable actuators. This new coming product has already been announced at Actuator 2012 conference in Bremen. Noliac expect a significant growth in sales from such improved materials as currently a lot of customers are asking for better reliability at high humidity.

The new manufacturing method for IDE actuators are expected, after some more engineering work, to be fully integrated at Noliac production facilities. Noliac plan to raise the necessary capital for expansion of production facilities and equipment for the new IDE actuators. A marketing plan will be developed for introducing the new IDE actuators to a broad range of segments e.g. the automotive, windmill and aerospace industries. Specifically, there is a tremendous potential for diesel and gasoline injectors (> 10 millions actuators per year) and provided that very low cost manufacturing of low voltage IDE actuators has been achieved Noliac will consider establishing a complete new manufacturing site in the Eastern Europe.

Jozef Stefan Institute

JSI will contribute with research in synthesis procedure for PZT powders and piezoceramics. JSI expects IPR to be generated in powder synthesis design by using measurements of zeta-potentials as function of the suspension pH by electrophoretic light scattering technique, granulometric analysis, X-ray diffraction analysis and electron microscopy.

Ecole Polytechnique Fédérale de Lausanne

EPFL expects IPR to be generated in improved PZT material compositions with increased fracture toughness. This will lead to piezoelectric devices capable to face high stress and humidity conditions that are beyond reach with the present state of the art materials.

Technical University Darmstadt

TUD has contributed in the innovation process in three areas:

a) suggestions for new, stress and humidity resistant materials

b) suggestions for new electromechanical poling techniques which reduce strain incompatibility strongly and therefore stresses in the actuator strongly.

c) suggestions for multilayer geometries with reduction in stresses for piezoelectric materials.

These innovations will be shared with other groups and planned to be patented inside the consortium.

The project has established one or two new lines of PZT actuator materials and one new line of actuator design. Based on both of these achievements, PZT actuators will be established in the marketplace for 2-3 new applications.

This will provide new jobs for engineers but also for skilled and unskilled personnel. The multi-national research force is based on existing contacts as well as new contacts. Both are necessary to use an established line of contacts but also to bring fresh new ideas in. Hence, new innovative proposals for future work will result from a successful consortium as this. Establishing several new product ideas will broaden the interest in smart materials and will strengthen the European base on actuators, which is already leading worldwide.

Noliac Ceramics s.r.o.

NC expects to be able to produce piezoceramic materials suitable for piezoceramic actuators resistant against cracking and humidity. NC expects that production technology and processes of new powders and bulk ceramics will be the point of IPR in the near future. The development of powders for multilayer actuators will significantly increase the competitive advantage in face of American and Asian companies.

It can be expected that development of such powders will increase the quality and the competitiveness of also piezoceramic elements which NC currently produces for example elements for ultrasound cleaning and welding and other elements which are working in extreme conditions (high mechanical or dynamical stress, high electric field, environment with high humidity and dustiness.

It will afford opportunity to develop and to use piezoceramic elements in applications in which it wasn’t possible before.

IPU

IPU has gained significant knowledge in the area of electroplating of thin metal wires during the HIPER act project. The expertise gained is expected to be of great benefit for the ongoing commercial activities at IPU within the field of electroplating of small metal components.

Gwent Electronic Materials Ltd.

GEM will combine its new materials technology with matched shrinkage characteristics to match metals to ceramics to increase stack or layer height. GEM will also work with much denser metal powders and advanced polymer technology to produce fine line definition interdigitated structures. This can be used in conjunction with fine line printing and stencil printing techniques and/or other techniques such as Direct Write.

Tecan Ltd.

Tecan envisages increased competitiveness arising from enhanced capability in the manufacture of fine deposition masks. This would lead to the manufacture of new produces in the general printing and surface mount assembly market, and medical device product area.

Competitiveness would also be gained by the increased capacity that the measurement systems we are proposing to develop could offer. Other potential product spin offs would be based on the general enhancement of knowledge which this project offers us and the effect it would have on our general micro parts manufacturing. Creation of new markets possibility 5 to 20 extra jobs in the next 10 years.

Tecan expects:

- Increase accuracy of printer masks, improved measurement capability, leading to increased sales in this area. IPR would be around fast accurate measurement of the fine mask structures.
- Increased competitiveness arising from enhanced capability in the manufacture of fine deposition masks.

DTU Wind Energy

DTU Wind Energy design and construct a trailing edge flap mechanism and tests its performance. Based on the measurements, wind turbine simulations will be carried out to indicate the expected decrease of load on wind turbines. Design, construction and test of the trailing edge flap and the results from the simulations will be reported

Vestas Wind Systems A/S

Vestas expects benefits from the project include an increase in energy efficiency and ▯ most important ▯ a substantial increase of the design lifetime of wind turbine due to reduces fatigue load. Currently, the design lifetime is 20 years.

By the end of the year 2004, approximately 48GW wind power was installed globally, corresponding to about 100.000 jobs. It is estimated, that the installed wind power will increase to 1250GW by the year 2018, which will mean at huge expansion of this industry and a corresponding improvement for the environment.

An estimate of the impact 5 years after successful end of the HIPER-Act project, is a 5% reduction in cost pr. energy and 25-35% increase in work force at Vestas (13.825 employees June 2007). Further it is expected to gain a substantial reduction in both fatigue and extreme loads on wind turbines.

It is currently being assessed in Vestas if the specific type of actuators developed within the HIPER-Act Project is suitable for WTG (Wind Turbine Generators) technology.

Leibniz Universität Hannover

LUH expects IPR to be generated by research in the machine dynamics of wire bonding machines. This will be investigated by means of finite element models and elastic multibody systems. Specific expectations:

- Fully active and passive vibration control systems for ultrasonic transducer and other semiconductor manufacturing machines.
- Real-world application of our piezo and vibration knowledge in a demonstrator

Hesse &Knipps GmbH

H&K expects a high potential benefit for the semiconductor production technology and in particular for ultrasonic wire bonding. The challenges are:

- Extreme high load cycle of up to 3e11 per year (300 Billion per year or more than 1 Trillion in 4 years) at high mechnical stress cause extreme high reliability requirements
- Microscale design of actuators

Our expectations to the introduction of piezoelectric actuators for active vibration control are:

- Improved bond quality, higher productivity
- Extreme high reliability, especially crack resistance
- Very high dynamics, operation with more than 100 kHz (ultrasonic)
- High electromechanical coupling

The aims for the bonding machine industry are mainly increased productivity and high reliability. But there are evolving applications - like 3D packaging - where wire bonding without active vibration control might be almost not possible, because bond force control and applying perfectly aligned ultrasonic vibrations to the bonding area becomes crucial.

The International Technology Roadmap for Semiconductors (ITRS, www.itrs.net) predicts a further reduction in wire bond pitch which goes hand in hand with a reduction in chip size and chip thickness. This leads not only to very high demands on bond force control, but also to the need of reduction of the mechanical impact during bonding. Especially parasitic vibrations perpendicular to the desired ultrasonic vibrations can lead to insufficient bond quality and in extreme cases even to micro cracks, which in the end destroy the chip.

This aspect is also important for copper wire bonding, which is a technology presently rising up very fast and which will certainly become more and more important in the near future. Because copper wire needs higher bond forces and amplitudes the risk of damaging the chip or under-layers is increased. Therefore again reducing parasitic vibrations is desired.

Regarding Moore’s Law the density of integration meanwhile is no longer doubling every 2 year, nevertheless the requirements of the industry to double functionality in this time interval has not changed. To keep in compliance with the needs of the market, the density is no longer measured as a density per e.g. mm2, rather than a density in mm3. This can be achieved by thinning the chips and stacking them afterwards, to keep at least double functionality in the same volume unit. One well known problem in System in Package (SiP) is the overhang of thin chips, which occurs if chips have different sizes. One can easily imagine, having vertical vibrations during bonding on overhanging bondpads can massively hinder bonding or even make it impossible.

Other sectors which could profit from the technology development are sectors where high frequency (kHz range) resonant vibration transducers are used, like in ultrasonic metal and plastic welding, high performance ultrasound-superimposed milling and drilling machines, ultrasonic cutting etc..

A bond head with active vibration control could overcome the mentioned problems and furthermore will achieve better bond quality and reliability than bond heads with conventional technology, thus will be more competitive.

In its November 2010 edition, Chip Scale Review (www.chipscalereview.com) gives a directory of production wire bonder manufacturers and it seems probable that the 2 European manufacturers (among 9 worldwide) could increase their market share using the new technology developed in the project. The whole semiconductor market including power electronic devices has a volume of about 300 Billion US$. The growth rate forecast for 2013 is about 5% (www.wsts.org, www.sia-online.org). The market for wedge-wedge bonding (mainly aluminium wire) ▯ which is the core market for Hesse & Knipps GmbH▯has a volume of approx. 300 Million US. The adjacent ball-wedge bonding market (mainly gold and nowadays copper wire), in which very similar ultrasonic transducers are used, has a volume of approx. 1.8 Billion US$.

<u>Fraunhofer Institute - LBF</u>

LBF expects to develop new material models and modeling methodologies for knowledge based material systems (the methodology is supposed to be applicable even for other material types) which will be used in smart, high performance system design for various application scenarios. The methodology is intended to be integrated in LBF’s smart system design methodology.

Moreover, it is expected to considerably extend knowledge for developing innovative piezo hydraulic pump systems (e.g. for applications in exhaust gas after treatment) which can contribute to the reduction of NOx and also CO2 emissions, thus enhancing the competitiveness of cars.

LBF expects that the project results will contribute to the development of innovative high power piezohydraulic pump systems (e.g. for electro-hydraulic, on demand braking) which indicate to have a surplus value for the reduction automotive system weight and finally CO2 emissions, thus for competitiveness of cars. This must be considered having a clear vision on the meaning of automotive industry for European employment, especially when considering the increasing Asian pressure on that market, now coming from China and India.

LBF is expecting to play an increasing role in the RTD and even design for such active engine mounts and will also extend their endeavours to other applications such as machine mounts.

LBF expects to develop new methods and strategies for system reliability investigation of active material systems, containing accelerated test methods as well as qualitative methods like FMEA adapted to the peculiarities of systems containing piezoelectric elements.

<u>ContiTech Vibration Control GmbH</u>

CTVC expects an increasing demand for active engine mounts for modern automotives. CTVC and LBF strategically cooperated in this project to develop that technology, which can also be used for commercial exploitation.

CTVC expect that new motor concepts (hybrid drives, etc.) and weight reduction concepts will increase the vibration levels within automobiles. This will increasingly be approached by active structure concepts exploiting knowledge based materials, especially piezo technology presumed that its price and robustness is compatible with specific automotive demands-, such as active engine mounts. Whereas especially in Asia certain active concepts for motor mounts have tested and even commercialized, this is still not the case for European stakeholders. Since the automotive industry (RTD, suppliers, OEM) is one of the strongest employers within Europe, it is essential that Europe catches up and develops innovative new systems. This potential seems tangible by exploiting piezo technology.

With respect to new drive systems within automotives vibration levels within the cars do increase. At the same time there is a permanent need to reduce system weight and emissions. Weight reduction is achieved by integrating new lightweight materials and design concepts. This again results in an increased sensitivity to vibrations. With respect to comfort, noise emission and material fatigue it is necessary to control vibroacoustic disturbances within the mechanical structure. One promising approach is to actively combat these vibrations at discrete locations by controlling the structure borne disturbances being spread from - predominately - the motor into the surrounding car structure. Thus, active engine mounts incorporating piezo actuators can itself serve as sort of standardized components to comply with new design requirements.

The project results has shown that it is possible to reduce noise and vibration by using the new piezo technology. The necessary design concepts were developed and tested. The project has driven the design rules of actuators and components and contributed to standardized test procedures for both. Thus the commercialization of hydro mounts containing piezo actuators became nearer.

One pre-requisite for the success of such active piezo engine mounts is the development of robust, low cost piezo actuators.

Ricardo Deutschland GmbH

Ricardo plan to increase know-how and gather experience with the principles of pump operation based on piezo-actuation (variability, response time, controllability, improved energy efficiency).

Useful and achievable Applications are identified in the field of exhaust gas after treatment for commercial vehicles. This will allow better adaption of the after treatment system to transient states of operation of the drive train thus increasing conversion efficiency and allowing to shift the NOx vs PM compromise towards higher NOx (engine out) and in consequence lower fuel consumption and CO2 emission.

Ricardo plans to develop a marketing plan for penetration of these systems. Ricardo plans to further develop the piezo pump single-handed or together with a manufacturer.

Ricardo is also pursuing other subjects in the field of exhaust gas after treatment for commercial vehicles which promise significant synergy with the projected goal for further development of the piezo pump, namely an intelligent fully variable unit injector for Adblue® (SCR NOx after treatment) and diesel fuel (DPF regeneration).

Ricardo has clients and research partner throughout the worldwide automotive industry and over 95 years experience in implementing innovation. Hence as soon as a project status is reached, Ricardo will start an initiative to approach tier 1 suppliers and OEMs intensifying contacts as the project progresses with encouraging results.

There are indications that actual product development and implementation of an important innovation are possible results of this project.

List of Websites:

http://www.hiperact.org/

Contact person: Jean Bruland

Noliac A/S

Hejreskovvej 18B

3490 Kvistgaard

Denmark

www.noliac.com