Reliability Analysis of Ultrasonic Power Transducers

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Abstract

While reliability has been studied worldwide intensively in the case of piezoelectric multilayer actuators - driven by car industry which now uses such actuators in their fuel injection systems - nearly no literature is available for the reliability of ultrasonic power transducers. As well, manufacturers seldom present data about ageing or lifetime of their components. To enhance the knowledge about typical failure mechanisms of ultrasonic power transducers under different load conditions, our contribution - as a first step - reports on a theoretical study on the reliability of common known ultrasonic transducers for different applications.

Key words: reliability, FMEA, ultrasonic power transducers

Introduction

Ultrasonic transducers are used in many industrial applications such as plastics or metal welding, bonding, machining, cutting, cleaning or chemical processes. During the setup of new devices or using standard equipment in uncommon environment (e. g. high humidity or temperature) it might happen that the transducers unexpectedly fail instantly or after some time of use. Often, such difficulties are solved empirically by trying other transducers, improved manufacturing technologies or changing driving parameters and boundary conditions (encapsulating, external cooling, etc.) without identifying the principal failure cause. This evidently leads to increased development or operating costs and sometimes deficient performance of the overall system.

Literature offers some information on failure mechanisms in piezoelectric multilayer actuators, as these have intensively been studied during the development of injection valves for car industry. As the main causes for performance loss or total electrical break down, crack building due to overstress in the non-electroded area, delamination of piezoelectric and electrode layers, and degradation by diffusion of electrode particles into the piezoelectric material were figured out ([1], [2], [3], [4]). Other studies report on the reliability of piezoelectric bimorphs that also suffer from cracks resulting from the bending action [5] leading to defective contact and thermal destruction of the electrodes in the crack surroundings [6].

In the field of ultrasonic diagnostics, reliability has also been an issue, but for ultrasonic power devices only very few information is available. This theoretical study will start to fill this gap by analyzing the principal structure of ultrasonic power transducers together with their application and control, figuring out typical failures and their impact on the overall system performance, and giving some hints how to avoid failures by construction, control or other measures.

Ultrasonic Power Transducers

Ultrasonic power transducers are most often bolted Langevin-type transducers composed of a bolt to pre-stress piezoelectric ceramics between a horn and a backing mass. The piezoelectric ceramics are electrically contacted by supplemental CuBe-sheets and the bolt is usually insulated against the ceramics and electrodes by a Teflon or heat shrinkable tube to avoid a flashover at high driving voltages. The design of the transducer is determined by the requirements of its desired application. Typical design goals are specified driving frequency, required velocity amplitude at the interface to the process or output power. Design parameters are the dimensions of the transducer, the material of the passive parts, and the type and amount of piezoelectric material. Figure 1 shows typical components of an ultrasonic power transducer before and after assembling.

Fig. 1: Typical design of ultrasonic power transducers. Top: Disassembled parts (steel horn and end mass, screw-bolt with insulating Teflon tube, piezoelectric discs, CuBe-electrode sheets); Bottom: assembled transducer

Characteristics and Control

Piezoelectrical systems are generally characterized by their electromechanical coupling behavior. For ultrasonic systems, especially the frequency-dependent ratio of driving current and voltage - the electrical admittance - gives information on the current state of the system. Figure 2 shows such a characteristic and its dependency on parameter changes, which might result from load changes, degradation or failure of the transducer.

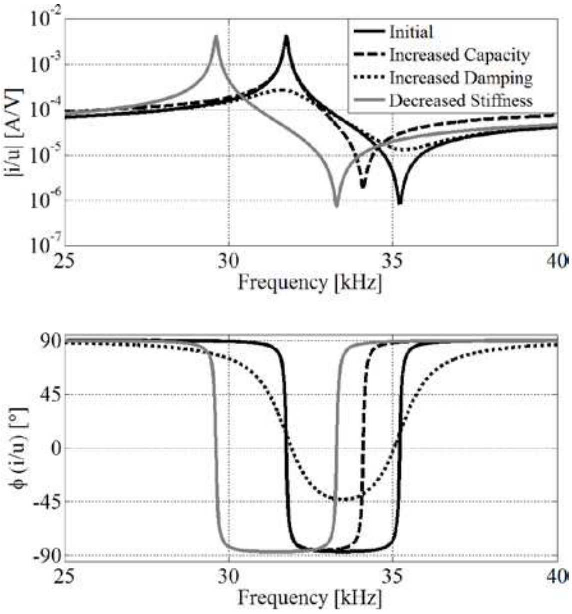

Fig. 2: Dependency of the electrical admittance of a piezoelectric transducer on system parameter changes

Ultrasonic transducers are most often driven in the vicinity of one of their resonances to achieve specified vibration shapes with high vibration amplitudes at low input voltage (resonance-mode) or current (anti-resonance mode). For low damped systems, resonance and anti-resonance frequencies are close to the frequencies, where the maximum and the minimum of the electrical admittance are found. As shown in figure 2, the increase of the transducers capacity, which might be due to heating, does not affect the resonance frequency but the anti-resonance frequency. An increase in the damping of the system, which can be a result of heating or due to degradation of the transducer, yields lower amplitude in resonance, higher amplitude in anti-resonance, and an increase in phase. At last, this means that more input energy will be needed to generate sufficient vibration amplitude. A reduced stiffness - as a result of crack formation or loose contact – significantly moves both frequencies.

As parameter changes do significantly influence the optimal driving frequency of the transducer, control algorithms are needed to reach sufficient amplitude. Low damped systems can be operated in resonance using a self-oscillating-circuit or by a phase-locked-loop-control (PLL). While a frequency shift can be well compensated in a limited bandwidth, increased damping might lead to failure as the phase characteristics flattens. This problem might be overcome by a load-adaptive phase-controller [7]. Another alternative is a maximum-admittance-controller that follows the peak of the admittance curve as long as a defined peak is detectable.

Failure Mode and Effects Analysis

For a detailed investigation of failures and their consequences a failure mode and effects analysis (FMEA) is advisable [8]. Therefor the failure modes of every item of the piezoelectric system including the transducer and its control are identified as well as the local and global effects of the failure modes. A small part of the FMEA is shown in table 1.

Tab. 1: Failure modes, effects, and causes for the piezoelectric disks within an ultrasonic transducer

Failure mode	Failure effect	Failure cause
crack formation	increased wear and damping, noise	mechanical overstress
depola-rization	loss of performance	temperature, electrical or mechanical overstress
pre-stress too low	increased wear and damping, contact loss, air pumping	bolt defect, wrong assembly, thermal extension

The main failure effect of ultrasonic power transducers is - as usual for active devices - a loss in performance. The measure of this depends on the kind of application: while systems generating ultrasound fields in air do mainly need high vibration amplitudes, processes like cleaning or welding do additionally need a high coupling coefficient to be able to transfer enough amount of power.

While the failure modes are few, the possible reasons for failures can be manifold. In case of the transducer, the main failures are a loss of pre-stress, cracks in the passive or piezoelectric parts, defects in the electrical bonds or increased friction between parts during vibration. These failure modes might lead to an immediate deficiency of the transducer (e. g. no electrical contact), to a failure in the control unit (e. g. loss of zero-phase crossing) or to lower overall performance so that the desired output cannot be achieved.

Case Study: Influence of Thermal Load

In Figure 2, the impact of certain system parameters on the characteristics of a transducer are shown. Typically, the parameters do not change independently and thus the effect on the characteristics is more complex.

As an example, thermal load effects due to operation at elevated temperatures or due to self-heating lead to a variation of material parameters - especially those of the piezoelectric discs - and to thermal expansion of the components, which affects the pre-stress, if the expansion of the screw and the pre-stressed elements are different. In turn, a change in pre-stress alters the stress dependent material parameters of the piezoelectric discs, and in case of pre-stress loss increased slip between the elements leads to higher system damping. Figure 3 shows the effect of a temperature load on the characteristics of an ultrasonic transducer.

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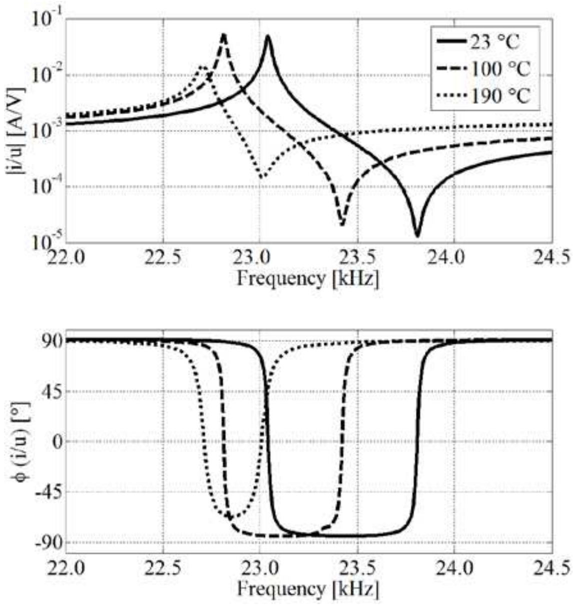

Fig. 3: Effect of temperature load on the electrical admittance of a piezoelectric transducer

From a comparison of figures 2 and 3 it becomes apparent that a temperature load simultaneously leads to a change in capacity, damping, and stiffness. To quantify the different changes, system parameters have been identified from the admittance characteristics based on fitting characteristic frequencies and amplitudes of an equivalent electro-mechanical model, see table 2.

Tab. 2: Effect of temperature load on the parameters of the system

Param.\Temp.	**23 °C**	**100 °C**	**190 °C**
C [nF]	5	7	9
d [Ns/m]	50	47	120
c [N/µm]	6959	6821	6759

While the effect of rising capacity is well known and also given with material data of the suppliers, the other effects need more interpretation:

- Data for damping are often hard to find in literature, but it is not unusual that material damping increases with temperature. In this case, damping is decreased slightly at 100 °C but increased strongly at 190°C. On the one hand, this is due to strongly nonlinear material behavior of the piezoelectric disks as its polarization depends on temperature and mechanical pre-stress. On the other hand, the increased loss of pre-stress at higher temperatures leads to increased slip between the parts and thus additional loss.
- Piezoelectric material typically shows negative temperature expansion coefficients in direction of its polarization coupled with increasing stiffness. Metal stiffness typically decreases with temperature. As there is more metal than piezoelectric material in the transducer, a decrease of stiffness can well be explained. But the amount of decrease in stiffness can only be clarified by the knowledge that a temperature induced change in pre-stress also leads to a change of the stiffness of the piezoelectric material as well as to a change in contact stiffness between the pre-stressed parts.

Failure Detection and Counter Measures

As the electrical admittance of the transducer delivers almost any needed information, it should be measured throughout the operation of the system or at least time-by-time. By identifying the system parameters and other characteristic data online and comparing them to nominal or previous values, control parameters can be adapted to achieve a stable system operation. As well, with the knowledge of the interdependencies of different failure modes and effects, specific failure causes might be identified and counter measures can be initiated.

Summary and Conclusions

A systematic analysis of failure modes, effects, and causes facilitates the design of reliable ultrasonic transducers and their stable operation. In this short paper the formal procedure was described and a part of the results was presented. The main basis of the concept is an online identification of system parameters. As the parameters change, advanced control and safety mechanisms can react without need for intervention of the user of the system. Within future research the effects of different faults on the system parameters will be quantified and suitable control algorithms will be set up.

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