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1. Preface

This article is a current practice report and deals with vibration measurement, vibration calculation and vibration monitoring of piping components in chemical plants.

The objective of this article is to gain an appreciation of vibration induced fatigue as a failure mode for process piping and get a first impression on the current situation of risk mitigation in an engineering department supporting chemical plants on site.

Acc. to [1] causes of failure in industry are classified as follows:

- 26 % by degradation of material properties (e.g. loss of flexibility in flange gaskets and valve stem packing)
- 19 % by corrosion/erosion
- 11 % by vibration induced fatigue (about 80% to 90% of those vibration induced fatigue on small bore connections)

Causes of failure due to vibration induced fatigue can lead to major safety and cost implications.

Data [1] indicates that 60% of vibration induced piping failures could be attributed to non-identification of hazards

- At the design stage, or
- When modifying (debottlenecking) existing plant’s resulting in a “fix-as-fail” approach.

Vibration problems occur as follows:

- During commissioning of a new plant
- When changing the “steady state” process conditions on an existing plant
- Transient events over an extended period (“hidden threat”)

2. Vibration Mechanism

The following different excitation mechanisms are the major sources for excitation in chemical plants.

- Flow induced turbulence
  Typical examples are process equipment, partially closed valves, short radius or mitered bends, tees or reducers.
- High frequency acoustic excitation
  In a gas system, high levels of high frequency acoustic energy can be generated by a pressure reducing device such as a relief valve, control valve or orifice plate. Those excitations tend to affect safety related (e.g. relief and blow down) systems.
- Mechanical excitation
  Most problems are associated to reciprocating compressors and pumps.
- Pulsation (Fluid within a piping system exhibits acoustic natural frequencies)
  o Reciprocating machinery
  o Rotating failure / breakdown
  o Periodic flow induced excitation
  o Irregular or stochastic excitations
  o Start up or Shut down
3. Vibration Measurement

Vibration measurement is divided into the following 2 subsections.
- Fluid-dynamics measurement (inside the pipe)
- Structural dynamics measurement (on the outside)

3.1. Fluid-dynamics measurements

The important measuring variables for fluid-dynamics measurement are:
- Pressure
- Temperature
- Flow rate
- Composition of the medium

Most cases a measurement of the pressure fluctuation is adequate.

Most commonly used sensors are dynamic pressure sensors (manometers) based on piezo-principle in order to measure even small pressure fluctuations, regardless of the current static pressure in the pipeline.

The location of the sensors is very important and needs to be discussed with an expert.

3.2. Structural dynamics measurements

The important measuring variables for structural-dynamics measurement are:
- Accelerations $a(t)$
- Vibration velocities $v(t)$
- Vibration displacements $s(t)$

Acceleration's, vibration velocity and vibration displacement can be converted to each other.

In the most cases measurement of vibration velocity is adequate.

The following structural dynamics measurements are used:

- Measurement of forced vibrations during operation
  The goal of this measurement is to describe and evaluate the vibrations occurring during operation and finding the responsible root cause.

- Experimental determination of natural frequencies
  Experimental modal analysis is most commonly used in order to determine natural vibrations. The system is shock excited and the values for the response function are measured.

  Common methods for excitation are:
  - Impact excitation
  - Step excitation
  - Electro dynamic or electro hydraulic excitation
• Noise excitation

• **Reliability tests**
  This method is used, in order to check, if piping specialty components, such as special supports, shock absorber etc. are working properly.

Measurement devices for structural dynamics measurements are vibration pick-up devices according DIN 45669 or DIN ISO 5348.

Normal Case measurements are done in the frequency range of 1 to 50Hz.

The location of the sensors is very important and needs to be discussed with an expert.

For evaluation methods and results, see [1].

## 4. Calculation / Engineering

### 4.1. **In Theory**

During early design stage of project, the design engineer and the Pipe Stress Engineer identify those pipelines, which should be reviewed.

The Piping Stress Review Criteria [1] provides guidance in determining, what lines on a project shall require review by the Pipe Stress Engineer.

The final outcome of the stress review meeting provides the lines to be calculated with Caesar II (or other software tools) and a rough estimate on the number of hours required.

Another outcome of this meeting could be those lines, which need special considerations, in order to avoid negative effects such as water hammer or where a review of correct supporting is necessary.

Pigging lines in our plant’s are also an example for lines, which need to be reviewed very carefully.

In the light of vibration’s [1] mentions the following points:

- All lines subject to vibration’s (see G4S-0140-01 [2])
- All lines Subject to pulsation (see G4S-0140-01 [2])
- All lines connected to rotating equipment such as pumps, compressors, steam turbines etc.

There are many resources (guidelines & experts) available in DOW to be consulted, if questions arise.

### 4.2. **The Real Life**

Lines subject to vibration are not always detected in the early engineering phase.

Those lines are often detected, when the plant is running and results are visible. In some cases, early information to the vibration expert is missing. Changes to be implemented into the design in a late stage are very expensive and difficult.

The layout of plants is not always communicated to the vibration expert.
For example: Centrifuges are located on top of the steel structure. A check of the resonance frequency between centrifuge and steel structure should have been performed in an early design stage.

5. Vibration Prevention

5.1. Brace everything

Additional supports can only be added after consultation of the piping stress calculator. It needs to be mentioned, that very often this does not provide a technical satisfying solution, as forces and stresses are higher than before.

5.2. Visual Inspection

This is most commonly used in plants. An example is the Pre-Start up plant walk. Unfortunately it is very subjective, there is no formal audit trail and cannot be used at design stage.

5.3. Monitoring (Structural Health Monitoring)

Vibration prevention by monitoring of piping components in chemical plants is not yet implemented. Only for critical machines is this a common standard.

The goal of monitoring pipelines and process equipment in the chemical industry is the extension of the life time, minimizing the number of LOPC and avoidance of serious incidents.

The goals above are also an integral part of the IRIS research project.

As the safety focal point for Engineering Solutions in the Rhine Center, I strongly support those activities.

5.4. Risk Assessment and Preventive Maintenance

This requires a high competency standard.

As an example, API RP 581 [3] is a guide line with 654 pages. Some advantages acc. [2] are the following:

- High risk areas identified for complete process and operational envelope
- Full audit trail
- Targets resources for visual inspection and measurement survey
6. Abstract

This short article deals with the current practice on vibration measurement, vibration calculation and vibration prevention in chemical plants. Improvement opportunities in early identification of hazards for vibration induced failures have been detected. Structural health monitoring of vibrating equipment is a very promising strategy for the future.

7. Literature Index

Preface

/1/ BUREAU VERITAS
Risk Based Approach to Vibration Induced Fatigue in Process Pipe Work / Presented to Dow Chemicals by Rob Swindell

Vibration Mechanism

/1/ MTD Ltd.

Measurement

/1/ Verein Deutscher Ingenieure
VDI 3842 / Vibrations in piping systems / June 2004 / VDI-Gesellschaft Entwicklung Konstruktion Vertrieb / Fachausschuss Schwingungen in Rohrleitungssystemen

Calculation / Engineering

/1/ Dow Chemical Company

/2/ Dow Chemical Company
G4S-0140-01 / Design and maintenance Inspection of piping systems subject to Vibration / Dow Chemical Company / 31-March-2007

/3/ American Petroleum Institute
/4/ American Petroleum Institute
API Standard 619 / Rotary-Type Positive Displacement Compressors for Petroleum, Petrochemical and Natural Gas Industries / December 2004 / American Petroleum Institute

/5/ American Petroleum Institute

/6/ MTD Ltd.

/7/ Wachel; Morton; Atkins
Piping Vibration Analysis / Turbo Machinery Laboratory; Department of Mechanical Engineering; Texas A&M University / 1990

/8/ Acoustic Technology Limited

/9/ Verein Deutscher Ingenieure
VDI 3842 / Vibrations in piping systems / June 2004 / VDI-Gesellschaft Entwicklung Konstruktion Vertrieb / Fachausschuss Schwingungen in Rohrleitungssystemen

Monitoring

/1/ Dow Chemical Company

/2/ BUREAU VERITAS
Risk Based Approach to Vibration Induced Fatigue in Process Pipe Work / Presented to Dow Chemicals by Rob Swindell

/3/ American Petroleum Institute
8. Active Vibration Absorbers for Industrial Piping Systems

8.1 Introduction

Different methods for vibration reduction in industrial piping systems can be considered. Due to safety requirements, up to now only passive methods like detuning, damping or passive absorbers are allowed. However, a lot of cases exist where those passive methods are not sufficient. Therefore, in a European R&D-project Safe Pipes, Project N° FP6-STRP-013898, Contract N°: NMP-CT-2005-013898, after intensive measurements in a chemical plant a demonstrator for active vibration reduction device for piping systems was developed. The demonstrator is based on the principle of an active vibration absorber, AVA, which is mounted onto the piping. The AVA is based on a 2 DOF active system that is able to reduce vibrations over a large frequency range. For verification of the vibration reduction potential of the AVA tests were carried out. The test results concerning the vibration reduction are very convincing. It was possible to reduce the amplitudes up to 80 percent.

Therefore, based on the patented AVA principle, within IRIS an up-scaling of the AVA and additional research work concerning safety concepts for active devices in chemical plants is planned. The objective is to reduce the safety risk of active devices to that it becomes possible to use it also in chemical plants.

One method to use active devices in plants consists of the application of an Active Vibration Absorber which is mounted onto the piping. The AVA’s function is based on the principle that an accelerated inertial mass generates a reaction force in the supporting structure:

\[ F = -m \cdot \ddot{x} \]  

The reaction mass is connected to the structure by means of a spring. An actuator is located parallel to the spring. By accelerating the reaction mass, using the actuator in combination with an appropriate control algorithm, a resultant force for vibration reduction is obtained.

Two straightforward control strategies are Acceleration Feedback and Direct Velocity Feedback. Acceleration feedback is implemented in combination with an Active Tuned Mass Damper (ATMD) \[1\]. The ATMD’s natural frequency is tuned to one natural frequency of the structure. But vibration reduction is only effected at that natural frequency.

A broadband vibration reduction can be achieved by using a Proof Mass Actuator (PMA) and Direct Velocity Feedback \[2\]. Here it is essential that the PMA’s natural frequency is significantly below the system’s first natural frequency.

8.2 Design

To achieve an observability and controllability of all vibration modes perpendicular to the pipe axis, the AVA is designed as a 2 DOF system, see Fig. 1. The two identical units of the AVA are oriented perpendicular to each other and are connected by means of a rigid connection. Via this connection the same reaction mass is obtained for both effective directions.
Consequently lower actuator strokes at the same total weight are needed.

![Fig. 1. Active Vibration Absorber](image)

The major part of the reaction mass is provided by the actuator magnets (Fig. 2 e). For actuation two electro-dynamic voice coils are used. These custom-designed actuators provide a constant force of 110 N (330 N peak force) and a stroke of 20 mm. The actuator's magnets and coils are guided relative to each other by an adjustable linear bearing that is free of play (Fig. 2 d). The coil is connected by means of a frame (Fig. 2 c) to the fixed part of the linear bearing.

![Fig. 2. Active Vibration Absorber unit I](image)

This frame is connected via leaf springs (Fig. 2 f) to the interface (Fig. 2 g) that is attached to the piping. The interfaces are clamped to the pipe with a tension belt (not shown).

The leaf springs perform various tasks:

- Provide compliance of each AVA-unit perpendicular to the actuators effective directions
- Guiding of the AVA-units in the actuators effective directions
- Transmission of the reaction forces to the piping
- Acceptance of the reaction mass’ static load

By varying the thickness of the leaf springs, the AVA’s natural frequencies can be tuned. By means of the setting mechanisms (Fig. 2 a) and (Fig. 2 b) the center positions of the actuators are adjusted. The setting mechanism (Fig. 2 a) is also used for adapting the AVA to different pipe diameters.
8.3 Mode of Operation

The AVA is designed to be actuated in two modes of operation independently. Both modes have in common to perform a vertical and horizontal motion and to use two accelerometers mounted on the pipe interface (Fig. 2 b). For each motion direction a separate decentralized controller is used.

Operation mode 1 is demonstrated in Fig. 3. The static load is accepted by the leaf springs of one AVA unit. The natural frequency in vertical and horizontal direction can be tuned differently. The preconditioned sensor signals are supplied directly to the appropriate controller and the actuators are driven separately.
Operation mode 2 is demonstrated in Fig. 4. The static load is accepted by the leaf springs of both AVA units. For vertical motion both actuators are driven by an identical signal, for horizontal motion by an identical signal with opposite sign. The preconditioned sensor signals are separated into vertical and horizontal components and supplied to the appropriate controller.

8.4 Experimental Investigation

For experimental validation a prototype of the AVA was manufactured. The AVA has a total weight of 16.25 kg; the weight of the reaction mass makes up 12.25 kg.

Likewise a testing structure was designed consisting of a pipe segment, connected to a steel frame that is supported by coil springs. The testing structure was loaded with massive concrete slabs to achieve a wide modification of the system characteristics, see Fig. 5. The weight of the testing structure and each concrete slab made up 25 kg. For excitation of the testing structure a shaker with a reaction mass of 35 kg was used.
The presented experimental investigations were realized in operation mode 2. The AVA’s natural frequency in both directions was set to 3.2 Hz. Control filters for the decentralized controllers were designed with the target to reduce structural vibrations in a wide frequency range (see Fig. 6).

The testing structure was excited in a range from 1 to 20 Hz. Figs. 7 to 12 show the control performance in vertical and horizontal direction with different setups of the testing structure, by using the same controllers. The number of concrete slabs was varied from one to six, with a total weight of the testing structure from 85 to 210 kg. The tests with deactivated controllers were done with the AVA’s reaction mass clamped to the piping. A considerable vibration reduction is apparent for all investigated configurations in the examined frequency range.
Fig. 7. Control performance with one concrete slab

Fig. 8. Control performance with two concrete slabs
Fig. 9. Control performance with three concrete slabs

Fig. 10. Control performance with four concrete slabs
Experimental investigations on a mock-up of a real piping system were carried out at MPA Stuttgart. The results are comparable to those at the MPA which are reported in [3, 4].
8.5 Conclusion, Discussion

An Active Vibration Absorber for vibration reduction of industrial piping was developed. The presented AVA is about a 2 DOF oscillator provided with two electro-dynamic voice coil actuators and one reaction mass. The AVA was investigated on a testing structure under a wide variation of the systems natural frequencies. The developed decentralized controllers showed an excellent performance in the considered frequency range. Likewise could be demonstrated that the control performance was not sensitive even to distinct parameter changes of the structure.

Compared to common passive approaches for vibration reduction the AVA shows essential advantages. Tuned Mass Dampers (TMD) require a mass ratio of about 10 % to reach a good attenuation. Therefore TMDs often are unfeasible due to high static load. The AVA’s performance is independent of its mass ratio.

The application of passive dampers requires a fixed support, whereas the AVA can be attached arbitrarily to the piping without a connection to the ground.

8.6 Acknowledgements

This research was accomplished within the project SAFE PIPES, Safety Assessment and Lifetime Management of Industrial Piping Systems (NMP2-CT-2005-013898, Contract Number 013898), sponsored by the COMMISSION OF THE EUROPEAN COMMUNITIES.

8.7 References


9. Safety Assessment and Monitoring of Piping Systems in Power Plants

The state of the art [1-3] of structural diagnostics and condition monitoring systems (CMS, in-service on-line monitoring) in plant engineering depends on the type of plant. Pipes in chemical plants are monitored to check the mode of operation and important parameters, e.g. mass flow, internal pressure and temperatures. In general there are only few cases where CMS is used to prove the integrity of piping. CMS in conventional power plants emphasizes measurements of thermo-mechanical parameters [2].

Vibration analysis is a well-known tool to monitor safety relevant piping in nuclear power plants (NPP). However, there are many different systems applied as well. Concepts and procedures of vibration and lose part monitoring in NPP were evaluated in a German national study [3]. Available systems such as SYSFAC (France), OPDAS (Japan) are based on measuring operational parameters, systems like FAMOS and MUSYCS validate additionally surface temperatures and systems like GIMOP, CUSTOS and TÜV, monitor strains and displacements. Because of occurring damages in pressurized components, vibration monitoring started in the seventies in France, Germany and Sweden. Since 1994 there is a demand for vibration monitoring according to KTA safety standard 3204.

The necessity to monitor short-term damage parameters yielded in the development of COMOS used for that part of monitoring which is useful for standardisation. SÜS (Schwingungs-Überwachungs-System developed by Siemens/KWU) complies with the monitoring rules and codes of KTA 3204, KTA 3201.4 and DIN 25475/2. The Monitoring System SIGMA (SIGnal Measurement an Analysis System) by ISTec is a mobile system used for the Primary Loop of Pressurized Water Reactors.

Similar to the diagnostic systems in the United States, Japan and west Europe, these vibration and lose part monitoring systems in NPP are also used in the eastern countries like Hungary, Czech Republic and Russia. For example, diagnostic systems are used in Hungarian nuclear power plants for the following monitoring tasks:
- Vibration monitoring (ARGUS, SÜS)
- Lose parts monitoring system (ELPIS, KÜS)
- Reactor - ambient vibration diagnostic (KARD, CARD)

The French vibration monitoring system PSAD (Poste de Surveillance et d'Aide au Diagnostic) was developed to control on-line relevant parameters of the main components of the primary and secondary loop. Additional modules enable the system to check lose parts and core components. PSAD is currently used in the French NPP TRICASTIN. EDF, SEMA Group and FRAMATOME have developed this system to increase safety and the availability and to cut costs by condition-based maintenance as well.
10. Experiences with Vibration Analysis and Model-Updating of Piping

The following was experienced during research activities [4-8], summarized in NED paper [9]:

The potential of the technical diagnostics of piping systems using modal analysis with ambient and artificial excitation was examined by means of laboratory tests and three real piping systems. The measurements at ambient excitation showed signals with significant peaks in the frequency spectra, even at low excitation, that significantly stick out from the basic noise. Supports in the failure condition were identified via shifting of natural frequencies or modified mode shapes.

Connecting stiffness to other systems (containers, walls etc.), elastic constructions of struts and spring hangers as well as stiffness parameters of wall penetrations were determined - respectively verified - with linear calculation methods (model analysis and model-updating).

In other cases, if the concerned piping is influenced mainly by energy dissipative supports like constant hangers or dampers, the updating of the parameters was carried out in the time domain by means of time history calculations. Thereby it was observed that the energy dissipation caused by friction during cyclic loading in constant hangers, fig.1, can be described well by means of an easy contact model with friction using calculations in the time domain. The Kelvin-Voigt-model is sufficient for viscous dampers, in order to achieve an adequate agreement between calculation and measurement.

The next step was to update system stiffness by commercial available model-updating programs on the basis of experimentally determined modal parameters. The quality of the results was evaluated using the so-called Modal Assurance Criteria (MAC-Matrix). If only very few mode shape pairs can be used for model-updating, a further improvement of the agreement calculation-measurement can be achieved by transferring starting values for model-updating from other similar bearing constructions.
When a main steam-line (FD-line) of a large nominal diameter in a conventional power plant was measured, modal-updating was difficult because of interactions between steel-construction and piping. A support of this FD-line, assumed as a fixed-point by the design, did not act as such. Here it had to be concluded that the supporting construction must be included into the calculation model.
The measured natural mode shapes of an emergency coolant piping corresponded to the ones of the design calculation primarily only partly - also in the number modes. A conclusion could be drawn from the experimentally determined mode shapes that additional clamping effects were present. The experimental modal analysis showed clearly, that the piping in horizontal direction is mounted stiffer than expected. In the design calculation stiffness for twin strut supports were given for vertical degrees of freedom only. Model updating showed that in this case stiffness had to be taken into account not only - as commonly simplified - for the vertical degree of freedom but also for additional degrees of freedom. After this measure the mode shapes also corresponded to those of the measurement [8].

The model-updating for a residual heat removal system lead to the quantification of connecting stiffness to a vessel that in the design calculation beforehand was assumed to be a fix point, fig. 2. The updated model yields realistic torsion support stiffness around y-axis with 4.5 MNm/rad.

**Comp. Measurement / Calc. after Model-Updating**

Measurement: 4.0 Hz  
Calculation: 4.01 Hz  
(Design-Calculation: 4.88 Hz)

**Example: Connection to a vessel:**  
Design calculation: constraint E1 = FP;  
After Model-Updating: HY(E1)= 4.5 MNm/rad

The examinations of the influence on the excitation intensity resulted in the following suggestion: Generalised damping values according to codes and standards (e.g. D = 4%) shall not be applied in all cases. High damping values identified immediately after large system excitation signify in particular cases that 'unnecessary conservatism' still exist.

Additional know-how on load carrying behaviour, reduction of vibration levels by means of vibration absorbers, model-updating and system identification of piping systems was gained during an European Research Project called SAFEPIPES [9]. The emphasize of this project was dealing with system modelling and model-updating on the basis of measurements carried out by MPA and SAFEPipe-partners in the MPA laboratory (mock-up of a piping system) at a chemical piping reactor and a piping of a nuclear power plant.
The mock up of a piping system, fig. 3, was constructed at MPA Stuttgart as object for investigations and as demonstrator for the deliverables developed within the project. Several mock-up tests with different kinds of support configurations and components were performed:

- Conventional damper with bitumen,
- prototype of passive damper with none temperature dependent fluid,
- prototype of active vibration absorber for piping,
- prototype of passive vibration and
- flange construction under dynamical loading

Model-updating and system identification methodologies were carried out by several partners:

- Investigation of different influence parameters,
- damage detection and damage allocation and
- optimisation of technical diagnostics.

The current overall objective was a better understanding of the load carrying behaviour, reducing vibration amplitudes, assessment of remaining lifetime and implementing a structural health monitoring system (SHM) and decision support system (DSS). All investigated prototypes of new components for mitigation of vibrations met their requirements.

**Dimension of Piping Section**

- piping material: 15Mo 3 (1.5415)
- nominal diameter: $D_a = 219.1$ mm
- nominal wall thickness: $t = 17.5$ mm

Mounting Plate

MPA-Shaker
At a chemical plant vibration analyses, investigations on corresponding failure mechanisms and calculation analyses were carried out with the aim of integrity assessments and constructive measures for reducing vibration amplitudes to avoid

- nozzle cracks,
- leakages and
- cracks in instrumentation nozzles.

The upper part of the plant has much less rigidity, cross sections of the steel structure are smaller and the top part even rises above the structure, see fig. 4. The piping system is not covered by a building and so it is subjected to weather conditions like heavy storms in this area near to the North Sea and of course temperature changes. All these conditions lead to irregular stochastic vibration of the plant, which cannot be controlled easily by standard shop bought damping elements.
Therefore, extensive investigations and measurement campaigns have been carried out, fig. 5. To understand failure mechanisms endurance, limit load tests on plane specimens of the special applied material were performed.
Fig. 5: Measurement campaign with accelerometers and seismic transducers

In-situ investigations at a piping of a nuclear power plant confirmed that it is possible to carry out vibration measurements in the low frequency domain below 30 Hz with transducers mounted directly on the insulation of the piping as it was experienced in former laboratory tests [6]. These measurements are useful for further model-updating procedures and integrity assessments of piping.
11. Fracture Assessment of Pipes Containing Cracks, Probabilistic Approaches

In the context of analysing the structural integrity of systems, fracture mechanics is an indispensable means for evaluating postulated or existing cracks in components. In these cases it is often required to quantify reserves in the load-bearing capacity for both - static and cyclic - loading. One worldwide accepted method for doing this is the so called 2-criteria approach', also known as the R6-method, which includes a so called Failure Assessment Diagram (FAD) [10].

This approach is in principle a method where the evaluation of the state of a component – safe/unsafe – is performed by using two load-related parameters,

- the stress intensity factor and
- the degree of plasticity.

The most important feature of the method consists in the fact that it encompasses both the linear-elastic (LEFM) and the elastic-plastic (EPFM) areas of fracture mechanics (see fig. 6). The curve depicted in the diagram, the so called Failure Assessment Curve (FAC), divides the (Lr, Kr) space into two regions. The points beneath the FAC are thereby considered safe, while the points above the curve can be regarded as unsafe. The points lying directly upon the FAC correspond hence to the states where crack initiation is to be expected.

On applying the method, the values called Kr and Lr must be determined, respectively. Within this context, the value Kr is given by the stress intensity factor K, normalized by the material dependent fracture toughness, while Lr represents the degree of plasticity of the ligament. These values depend on the type and amount of load, the properties of the manufactured materials, but also on the geometry of the component and of the flaw. Under the assumption that these values are constant, one can calculate the corresponding point within the (Lr, Kr) space and determine the state of the component based on the location of this point within the FAD (fig. 7). An increase of the load leads, by holding the other input parameters constant, to a linear translation of the state point along the corresponding line (see fig. 7).

As is generally known, the input values mentioned above are subjected to statistical variation. In order to be able to make realistic assertions concerning the state of a component, these variations must be taken into account while performing the computations. This is possible by extending the R6-method by probabilistic means [11]. However, thereby the exact position of the condition point would not be calculated, but a probability of failure assigned to it. Generally, this kind of failure assessment is computationally very expensive. Depending on which statistical approach is being used and how many parameters must be considered as statistically distributed input values, such a computation may require more or less execution time. Therefore, one is interested in finding alternative approaches. Related to this issue, it must be verified within the present work package, how and to what extent this problem can be solved by using artificial neural networks.

The artificial neural networks were proven to be an appropriate approach for some specific application areas. They are for instance widely used within the areas of image and (hand-written) character recognition, but also within the area of process monitoring. Some of the most important features of the neural approach are the ability to learn during a training phase and the robustness concerning noisy inputs, like e.g. the temporary failure of a sensor during
operation. Fig. 8 shows a so called feed-forward network and the structure of a node in a schematic manner.

![Diagram showing LEFM, EPFM, and Plastic Collapse regions](image)

**Fig. 6:** R6-Method - Failure Assessment Diagram (FAD) and different Fracture Mechanics regions

![Diagram showing limit curve and state space partitions](image)

**Fig. 7:** R6-Method – State Space Partitions (safe/unsafe)
Fig. 8: Artificial Neural Network (feed-forward); Structure of a Neuron
12. Literature


[9] Specific targeted European Research Project SAFE PIPES: Safety Assessment and Lifetime Management of Industrial Piping Systems, supported by the Commission of
the European Communities under the 6th framework program (NMP2-CT-2005-013898)


13. Introduction PFC Sensors and Actuators

13.1 PFC-sensors and actuators

Piezoelectric transducers are widely used in SHM. In chapter 0 we describe actual work on a new class of piezoelectric composite transducers (so called PFC-Patches) consisting of thin piezo ceramic fibres embedded in a polymer matrix.

13.2 Tunable Damping with ER-Fluids

Tunable damping is needed when resonance frequencies change e.g. due to changing operating conditions of machinery or civil structures. This can be done by adjustable hydraulic dampers with servo-valves or in a more simple way, using smart materials which change their viscosity in an electric field, so called electrorheological fluids or gels. Recently undertaken R&D-Tasks on this topic are described in chapter 0
14. PFC-Sensor and Actuator Development

14.1 Setup and Sample Preparation

Calibration of prototype piezo fibre composite (PFC) transducers with regard to strain vs. output charge was the focus of the present work. In contrast to ultrasonic techniques as guided waves or acoustic emission low frequency techniques like strain measurements and vibration analysis will need calibrated transducers in order to obtain well defined strain signals and thus an optimum reproducibility of the health monitoring output.

Sensor and actuator calibration is done by using calibrated strain gages, accelerometer and a vibration exciter (shaker) together with a function generator as signal source. For reproducible deflections (strains) of the transducer, triangular shaped steel beams were designed and fabricated. This was supported by simulations from project partner WBI.

PFC transducers were applied according to an internal standard procedure. The curing parameters for this procedure were the following:

- Curing pressure across the transducer: 1 bar
- Curing temperature: according to manufacturer instruction
- Curing time: according to manufacturer instruction

Calibration was than carried out under variation of:
- frequency
- temperature
- adhesive

The following diagram shows the low frequency behaviour of the setup measured via strain gage. The first resonance frequency at 270 Hz starts rising with a singularity (minimum) at 150 Hz. For frequencies between 20 Hz and 150 Hz the signal is proportional to the amplitude of the shaker. Thus, within this frequency interval the setup allows for calibration of the piezofibre transducers.
A calibration for higher frequencies was not necessary because in practice the interesting eigenfrequencies are clearly below 150 Hz.

The temperature variation was between room temperature (22°C) and 150°C which is the upper temperature limit for the PFC matrix and the piezo active PZT material.

Altogether about 16 samples have been investigated with regard to the parameters temperature, frequency and adhesive. For each sample a reference measurement, frequency variation and temperature variation was performed. The reference sensitivity was taken for 50 strain points between 0 and 350 ppm. Each point was measured 10 times for good statistics. Frequency variation was performed in intervals of 3 Hz. Every interval was measured five times. Temperature variation was carried out with 3 data points per Kelvin. Altogether, for each sample about 1150 data points were acquired and evaluated in order to obtain the present results.

### 14.2 Calibration via Strain Gage and Accelerometer

Following diagram shows the PFC charge signal compared to the strain signal of the gage. For vibration amplitudes near the strain gages sensitivity limit, the PFC still shows a very high signal/noise ration which is a factor 30-100 higher than that of the strain gage. The same applies for higher frequencies. In the order to get the most exact deflection and thus strain of the beam, the amplitude was additionally measured with an accelerometer. The strain was then obtained from the amplitude (two-fold integration of the acceleration signal) and the beam geometry.
A typical calibration curve is shown in the following diagram, where the PFC charge is plotted versus the “calibrated” strain.

The slope of this curve is the wanted sensitivity (=charge/strain) which in the following is measured under variation of capacitance, frequency and temperature. The reference is specified to be recorded at 22°C and a frequency of 47.75 Hz. All variations will be plotted as deviation from the corresponding reference value.

### 14.3 Sensitivity vs. Capacitance

The result of the sensitivity variations as a function of the low-level signal capacitance (at 22°C and 1 kHz) is shown in the next diagram. Both, temperature and frequency were held constant at 22°C and 47.75 Hz, respectively. Capacitance variation was due to the tolerance of the prototypes. The geometry was the same for all tested PFC samples. Capacitance variations between the PFC samples show a variance of ±20 % around a mean value of 1.1nF. For a given capacitance an average sensitivity variance of 10% was observed in the present data. Within this variance, no significant difference between the sensitivities was observed for different adhesives at reference conditions.
The following function was fitted to the reference data:

\[ Sensitivity[nC / ppm] = 0.8 \cdot C_p^{1.64} [nF] \]

This function applies for the standard PFC geometry and can be used as a good approximation of the sensitivity in the diagrammed range when no calibration is available. Deviations from this reference characteristic due to other frequencies or temperatures are specified in the following.

### 14.4 Frequency Variation

The following viewgraphs show the sensitivity deviation as a function of frequency for the standard PFC samples with SK and 2KK adhesive, respectively. Temperature was held constant at 22°C. At the reference frequency of 47.75 Hz the deviation is zero per definition. Each graph represents an average characteristic from the stated number of samples.
Both diagrams show a similar decay towards higher frequencies and could be fitted by a third order polynomial. The smaller decay of the SK-adhesive might allow for the fact of a higher stiffness and/or lower film thickness compared to the 2KK-adhesive.

The frequency dependence of HK-adhesive was not reproducible and for the time further analysis is being disclaimed.

### 14.5 Temperature Variation

The next viewgraphs show the sensitivity deviation as a function of temperature for the standard PFC samples with SK and 2KK adhesive, respectively. Correspondingly, the frequency was held constant at 47.75 Hz and as defined, the deviation is zero at the reference temperature of 22°C. According to previously, each graph represents an average characteristic from the stated number of samples.
Adhesive 2KK causes a continuous decay of the sensitivity towards high temperature, which in first approximation might be described by a linear curve. For adhesive SK however, the sensitivity varies only slightly around the rather flat slope of linear fit1 until about 100°C and from thereon decreases abruptly with the slope of linear fit2. Temperature dependence of HK-adhesive was not reproducible and hence no further analysis was executed.

14.6 Summary

Calibration of the sensors (strain vs. charge) with respect to frequency, temperature, and adhesive (application parameter) was completed successfully. An apparatus was set up to allow for a customized low frequency sensor calibration of each transducer under temperature and frequency variation. Also parameters like adhesives and application conditions play a role to the sensor characteristics. Latter was held constant in order to keep variation parameters manageable within the time-frame.
### 14.7 PFC Sensors, Data Sheet

<table>
<thead>
<tr>
<th>HP-PFC Properties</th>
<th>Symbol</th>
<th>Unit</th>
<th>Magnitude</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometric data of active area</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>l</td>
<td>mm</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>b</td>
<td>mm</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>d</td>
<td>mm</td>
<td>0.5</td>
<td>±10%</td>
</tr>
<tr>
<td>Fiber filling degree</td>
<td>εf</td>
<td>%</td>
<td>28</td>
<td>incl. insulation</td>
</tr>
<tr>
<td><strong>Low level signal at 1 kHz / room temperature</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance</td>
<td>C0</td>
<td>nF</td>
<td>1.4</td>
<td>±20%</td>
</tr>
<tr>
<td>Capacitance/area</td>
<td>C0/A</td>
<td>nF/mm²</td>
<td>0.18</td>
<td>active area only</td>
</tr>
<tr>
<td>Dissipation factor</td>
<td>tan δ</td>
<td>1</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td><strong>Electric properties at room temperature</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dielectric strength of isolation</td>
<td>Um</td>
<td>kV/mm</td>
<td>70</td>
<td>isolation thickness = 150 μm</td>
</tr>
<tr>
<td>Intrinsic dielectric strength</td>
<td>Umax</td>
<td>kV/mm</td>
<td>&gt; 4</td>
<td>electrode spacing = 0.5 mm</td>
</tr>
<tr>
<td>Insulation resistance</td>
<td>R</td>
<td>Ω</td>
<td>&gt;10⁻³</td>
<td>measured at 2 kV</td>
</tr>
<tr>
<td><strong>Electro mechanic properties at room temperature</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static stress specific charge sensitivity</td>
<td>ssq</td>
<td>pC/N</td>
<td>3640</td>
<td>±20% (for 29 mm entire width)</td>
</tr>
<tr>
<td>Static strain specific charge sensitivity</td>
<td>ssq</td>
<td>pC/μm</td>
<td>8175</td>
<td>±20% (for 29 mm entire width)</td>
</tr>
<tr>
<td>Piezoelectric charge constant</td>
<td>d33</td>
<td>pC/N</td>
<td>280</td>
<td>±20%</td>
</tr>
<tr>
<td>Piezoelectric voltage constant</td>
<td>-q33</td>
<td>mV/mV/N</td>
<td>37</td>
<td>±20%</td>
</tr>
<tr>
<td>Open loop deflection @ 1.2 kV/mm @ 100 Hz</td>
<td>xo</td>
<td>μm</td>
<td>7.5</td>
<td>by acceleration measurement</td>
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<tr>
<td>Calc. blocking force @ 1.2 kV/mm @ 100 Hz</td>
<td>F0</td>
<td>N</td>
<td>83</td>
<td>from Young’s modulus</td>
</tr>
<tr>
<td><strong>Mechanical data at room temperature</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>E1</td>
<td>GPa</td>
<td>33</td>
<td>DIN EN ISO 527 (in fiber direct.)</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>σT</td>
<td>MPa</td>
<td>210</td>
<td>DIN EN ISO 257</td>
</tr>
<tr>
<td>Strain at failure</td>
<td>εf</td>
<td>%</td>
<td>2.8</td>
<td>DIN EN ISO 527</td>
</tr>
<tr>
<td>Interlaminal shear strength</td>
<td>τsλ</td>
<td>MPa</td>
<td>29.5</td>
<td>DIN EN 65148</td>
</tr>
<tr>
<td><strong>Temperature behavior</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyroelectric charge coefficient (25...80°C)</td>
<td>Qd/t</td>
<td>nC/K</td>
<td>20</td>
<td>laminated to C-FRP</td>
</tr>
<tr>
<td>Maximum temporary temperature</td>
<td>T_max</td>
<td>°C</td>
<td>180</td>
<td>without shear stress</td>
</tr>
<tr>
<td>Maximum permanent temperature</td>
<td>T_max</td>
<td>°C</td>
<td>110</td>
<td>recemond</td>
</tr>
<tr>
<td><strong>Fatigue rate @ ±1.5 % @ open circuit</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance decay after 10³ cycles</td>
<td>C0-C0/Cre</td>
<td>%</td>
<td>7</td>
<td>laminated to C-FRP</td>
</tr>
<tr>
<td><strong>Sensor properties at 22°C / 47.75 Hz</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge sensitivity vs. capacitance</td>
<td>sC / C0</td>
<td>C/ppm</td>
<td>0.81 x C0[F]</td>
<td></td>
</tr>
<tr>
<td>Frequency variance</td>
<td>Δs3 / s3</td>
<td>%/Hz</td>
<td>-0.25</td>
<td>0...60 Hz (to average)</td>
</tr>
<tr>
<td>Temperature variance</td>
<td>Δs3 / s3</td>
<td>%/K</td>
<td>-0.67</td>
<td>20...150°C (to average)</td>
</tr>
</tbody>
</table>
15 Intermediate Results Obtained by the Structural Health Monitoring System

15.1 Support of Sensor and Actuator Application on Different Demo-Platforms and Field Studies

The fabricated prototype PFC transducers were tested in various field studies at DOW and RWE Plant, on a test structure and the mock-up.

Figure 1: SHM pre-examination tests at DOW-Plant.
Measurement techniques like low frequency vibration analysis, impact analysis and guided wave analysis were performed by WBI and IZFP and supported by NMW. From supporters point of view the most outstanding features of the PFC transducer for the SHM system are excellent handling and extremely high sensitivity. For guided wave analysis no calibration is necessary. On the other hand, a specific calibration is necessary for strain, vibration and impact analysis in order to get maximum information about health conditions.
16 Prototype of Structural Health Monitoring System

16.1 Prototype PFC Transducers with Embedded Signal Processor for SHM System

A sensor PFC transducer layout with embedded signal processing (controllers, charge/voltage amplifiers) was developed and prototypes were fabricated by NMW and tested. The sensory system allows for process of local and global signals in the low frequency range (modal / resonance / strain analysis) and high frequency range (guided wave / acoustic emission analysis). Outstanding features are a very high robustness and a custom-made user-friendly technology.

Figure 4: New prototypes of PFC ultrasonic guided wave transducer and prototype SHM system (NMW).
Figure 5: PFC prototypes with embedded amplifier electronics (NMW).
Figure 6: Prototype SHM System (NMW).
17 Tunable Damping with Electro Rheological Fluids

17.1 Introduction

Although the Electro-Rheological (ER) effect was discovered early in 1949 [1], its wide application in physical components or systems did not take place until very recently. This is mainly due to two reasons: (a) the lack of suitable voltage amplifiers (power supplies) of reasonable cost and able to supply the high voltages required for operation and (b) certain physical limitations of the ER fluids. R&D effort has focused for several years on resolving these two technical issues and has succeeded in developing and marketing commercially acceptable ER fluid-based controllable dampers for use in medical rehabilitation and exercise equipment, industrial vibration isolation systems and in automotive vehicle suspensions [2].

Figure 1: Tunable ER-Dampers, with integrated electronics for industrial application.

17.2 Materials and Processing Development

For commercial use in industrial or high volume applications the requirements for the used ER-Fluid are:

(1) Robust ER fluid and complete systems, meaning high resistance to wear and abrasion as well as long-term stability of the fluid

(2) Sufficient yield stress and “turn on ratio” to allow for compact devices (wide dynamic ratio of damping force)

(3) Fast response to applied signals

(4) Low power consumption for efficient energy use and for lowing the cost of the high-voltage power supply
(5) Wide operating temperature range and flat ER-response over this range

(6) Use of standard materials, which are widely available and inexpensive

Recently, we published [3] several technical developments that have raised the performance of Electro-Rheological dampers based on a high-volume production fluid to a new level. Some details about the latest technical advances of the Fludicon ER-Fluid “RheOil” [4] will be published soon [5]. They are summarized below.

“RheOil” consists of polyurethane particles (microspheres with a mean diameter of approx. 5 micrometers) dispersed in silicone oil. Using these rather soft polymer particles offers certain unique advantages. Starting from standard raw materials and a proprietary integrated “polymer in emulsion” processing technique, the particles (and therefore the whole ER-dispersion) can be adjusted with respect to various aspects:

(1) The use of off-the-shelf available raw materials and the easily scalable processing allow for a cost-effective production in all amounts

(2) The size of the particles as well as their size distribution can be adjusted to obtain optimum ER performance [6]

(3) The polarizability of the particles can be adjusted via dopants to a level which is appropriate for a certain application, giving a speedy ER-response as well as high yield stresses

(4) The integrated processing allows for the introduction of a chemically attached surface-modifier, resulting in low sedimentation rates and excellent remixing properties [7].

Based on the possibilities of this manufacturing process, the ER-Fluid development was carried out: (a) by choosing the right chemical composition of the ER-fluid and (b) optimizing the processing parameters. The main focus has been on:

![Fig. 2: Photograph and schematic of the manufacturing process in 4 steps. (1) Make emulsion of Silicone-Oil droplets in Polyol. (2) Add more silicone-oil until phase inversion takes place. (3) Mix polyol-droplets in silicone-oil until they are of right size. (4) Add hardening agent to form solid PU-particles.](image)
1. Optimizing the yield stress and the so called “turn on ratio” over a broad range of temperatures

2. Reducing the power consumption for controlling the ER fluid

3. Enhancing the sedimentation & remixing behaviour

Due to the level of the electrostatic forces active in an ER fluid, these fluids generate relatively low yield-stresses (typ. 5-10 kPa) in their fully energized state as compared to Magneto-Rheological (MR) (typ. 50-100 kPa). One effort to increase the ER effect, reported by Wen and co-workers [9], formulated a “Giant ER-Fluid” with a yield stress of up to 250 kPa at 5 kV/mm. However, a closer look reveals that its turn on ratio (\((5\text{kV})/(0\text{kV})\)), which is a measure for the dynamic range of the Fluid and is also determined by the base viscosity, is in the same range than other ER or MR fluids (approx. 20).

For the “RheOil” development we concentrated on a very low base viscosity (30 mPa.s) of the dispersion, together with a reasonably good yield stress to get a good turn on ratio (approx. 20) over a broad range of temperatures. The low base viscosity also allows for a compact design of “fast moving” devices like car dampers or industrial brakes.

![Fig 3: Yield stress at E = 0 kV/mm (orange) and E = 5kV/mm (red) and turn on ratio (blue) over a broad range of temperature.](image)

Although the nowadays used ER fluids belong to the class of inhomogeneous ER fluids (dispersions of particles) they exhibit a very low sedimentation rate, due to the fact that the particles and the liquid are well matched in density. Therefore, they combine the outstanding long-term properties of homogeneous ER fluids, such as like liquid-crystal based fluids [10], together with much better ER performance (faster response, larger yield stress) of particle-based ER fluids. This potential can be realized if the remixing property after an extremely long period of storage (and therefore separation of particles and liquid due to small differences in density) is enhanced. In the case of RheOil this is done by a chemically...
attached emulsifier, which equalizes the surface energy of particles (hydrophilic) and surrounding fluid (hydrophobic). Due to this emulsifier, which is extremely stable against mechanical or thermal loading, the particles do not form strong aggregates but rather a very soft sediment which can easily be remixed [8] by the flows induced inside the device.

Fig. 4: Sedimentation behaviour for “RheOil” (green circles) and an unstabilized suspension (red triangles, for comparison). The remixing time after 8 weeks settling was 16 seconds (RheOil) and 50 minutes for the unstabilized suspension.

### 17.3 Applications

Besides the series production of tunable ER-brakes for fitness and rehabilitation equipment (see Fig. 5) and the development of high-volume damping systems for the automotive industry, a strong effort was made on engineering of standardized controllable dampers for use in industry (see fig.1). These standardized dampers are available in various diameters (defining the maximum damping forces) and customizable length. For successful introduction of this new technology in industrial application or use in civil structures additional R&D has to be undertaken.
17.4 Summary

“RheOil” has been developed to specifically satisfy the demanding needs of industrial and automotive dampers in terms of long-term stability, thermal performance, low abrasion, light weight, enhanced turn on ratio and fast response characteristics. In parallel, the manufacturing process has been optimized for mid-sized batch operation and high-quality, consistent “RheOil” production.

Based on these ER-Fluids various applications, either in the consumers or the automotive market have been developed. Actual development concentrates on the application of this new technology in industrial areas like production machinery or for damping in civil structures.

17.5 References


17.6 Papers and Conference contributions

PAPERS published

CONFERENCES, SEMINARS, SYMPOSIA
1. Actuator 2006, Bremen, Germany (international conference on actuators)
2. Adaptronic Congress 2006, Göttingen, Germany (international congress on sensors, actuators and systems for adaptronics)