Gathering knowledge of the dynamic properties (natural frequencies, modal damping, modal shapes) is necessary to develop better products, characterized by lower noise emissions. The current developments on quality control in acoustics and vibrations do not provide enough usable parameters regarding the limits and tolerances of constructive parts. This shortcoming means increased significant costs for manufacturers.

With this novel hammer it is possible to measure, in an automatic and reproducible way, the dynamic properties of components such as brake pads, gears, small shafts, turbine blades... These parameters are helpful for the development of more silent products and to develop product and quality specifications, that later guarantee the series manufacturing of a silent product. With the Scalable Automatic Modal Hammer (SAM), the requirements for a commercial implementation of “automatic modal analysis” are fulfilled.

A fundamental research is going on to test and simulate lightweight structures for their optimization. Precise test input data for an accurate simulation is essential. However, the identification of the structural dynamic properties of lightweight jointed structures and composite material is a great challenge due to their non-linear behavior.

A Scalable Automatic Modal-Hammer (SAM) is developed, which leads to precise and repeatable excitation levels.

Structural dynamic properties of bodies or work pieces are expressed in terms of natural frequencies, modal damping and mode shapes. Most lightweight structures are jointed together or made of composite materials with complex geometries. For simulations the structural parameters like
Eigenfrequency, modal damping and modal stiffness are needed as input obtained from experimental modal analysis (EMA). Both models will be updated and validated (Fig. 1). However, EMA is a procedure that takes structural linearity for granted. As a consequence, if the structure presents a non-proportional force/response the simulation will be prone to failures. The application of the new developed scalable automatic modal hammer will give a solution to this problem.

Fig. 1: Validation of an analytical modal model with the experimental modal model.

Until now, manual hammers with integrated piezo-electric force sensors were used for modal experiments on this kind of structures. This is not only time-consuming, but also leads to different and unprecise force excitation levels (Fig. 2).

Non-linear structures and structures with non-proportional damping exhibit a non-linear spring characteristic. Impacts with different force level will lead to responses which are not proportional. Combining these measurement will lead to wrong results. By applying only one exact force level the frequency response function can be calculated for this given “working point” at this particular force level.

With the development of the Scalable (adjustable force amplitude) Automatic Modal Hammer it is possible to dynamically excite structures with precisely the same force amplitude and precise excitation point. With this exact repeatable force level only one point of a given non-linear stiffness characteristic curve is excited. This leads to an exact response signal from the structure (Fig. 3). Only by applying an impact with a precise and repeatable and controllable force level it is possible to study structures with non-linear structural behavior. This technique is possible with the new development. The results can be further used for the updating of simulation models or the validation of the simulation results (Fig. 1).

Fig. 2: 10 measurements at the same point of a non-linear brake pad with a handheld modal hammer. The differences in amplitudes and frequencies are obvious in the frequency response function plots.

Fig. 3: 10 measurements at the same point of a non-linear brake pad with the SAM. There are no measurable differences in amplitude or frequency on the frequency response function plots.

The combination of SAM with contactless a Scanning Laser Doppler Vibrometry leads to full-automatic, precise and cost-effective structural dynamics measurements (Fig. 4).
Fig 4: Modal test with the SAM and a 3D Scanning Laser Doppler Vibrometer at an aircraft turbine blade.

The innovative SAM makes possible:

- a reproducible and adjustable force input.
- a precise localization of the force input.
- an adjustable deceleration on the impact point to avoid double impacts.
- an adjustable impact angle.
- an adjustable idle time in between impacts.
- the elimination of double impacts that lead to measurement errors.
- the full automation of the measurement procedure.

A force-time plot of a measurement on a test structure is shown in figure 5, above. On the zoomed representation (fig. 5, below), the contact time of the hammer tip, of around 100 µs is represented. The adjustable low contact time Dirac impulse ($f = 1/T$), results in a quasi-linear frequency excitation spectrum of about 20 kHz. The maximum input power spectrum decrease less than -5 dB in the frequency range up to 20 kHz. (Fig. 6).

![Force/Time diagram of a structural measurement with the SAM](image)

![Contact time of the hammer tip (zoomed view): less than 100 µs.](image)

![Excitation power spectrum of the force signal plotted on figure 5.](image)

**Excitation Reproducibility**

The repeatability of the excitation force level is characterized by the different impact force levels shown in figure 7 and table 1. The SAM allows a maximum deviation of ± 4 N, with a standard deviation of 1 N. This is important for testing non-linear materials such as composite plates.
Any forced or free dynamic response of a structure can be described by a discrete set of vibrational modes. Each mode is in this case composed of 3 parameters: natural frequency, modal damping and mode shape. They can be extracted via the process of experimental modal analysis of the measured transfer function of a structure. The modal parameters of all modes form a complete description of the dynamic behavior of a structure.

\[ H_{ii}(\omega) = \text{Summe}_{m, r=1} (\phi_i(r)^*\phi_i(r) / \omega^2 + j\omega \sigma(r) + \omega^2 (r)) \]

In this equation, the modes are coupled among each other as summands. Each mode is expressed through three modal parameters and the mass-normalized mode shape, \((\phi_i(r))\), eigenfrequency \((\omega_i^2 (r))\) and modal damping \((\sigma(r))\). The application possibilities of modal data are extremely wide-ranging and include the cross-checking of modal frequencies, the creation of qualitative descriptions of the mode shapes (understanding of structural behavior for damage detection) and verifying and refining analytical models ("model updating"). The frequency response functions (FRF) of the structure are obtained on an EMA test. The FRF is defined as the mathematical division between output and input signals, or as system response vs. excitation.

\[ H(\omega) = X(\omega)/F(\omega) = \text{Output/Input} = \text{System response/Excitation} \]

The excitation should excite uniformly the entire frequency range of interest. This is achieved with a hammer impact; the transient excitation is measured by a dynamic force sensor at the hammer tip.

The controlled Hammer excitation is an excellent excitation technique that lets the structure vibrate freely and does not influe
ence the structure by coupling masses which distort the structural damping response.

The system response can be measured contactless, for example with Laser Doppler Vibrometer. An example of a measurement setup with 3D SLDV can be seen on figure 4.

A pre-requisite for a successful modal test is the assumption that the examined structure is a linear and time-invariant system. This means that the system must have a linear response and behavior, and must be time-invariant. These linear requirements are not inherent in complex assemblies with joints or composite materials. This leads to a non-linear spring curve. Changes on the force signal during a measurement lead to non-proportional response signals and to varying modal parameters. The curve fitting of Frequency response functions, impacted with scattered force levels like those in Fig. 2 leads to wrong results in damping, eigenfrequencies and mode shapes.

This effect can be well observed at the excitation signal resulted of a handheld hammer excitation on a brake pad, which has an inherently high variation on the force input. Figure 2 shows a sample of 10 FRFs. The system response was recorded with a LDV at a given point of the brake point, and the excitation at another point across the brake pad with a handheld hammer. The deviations on the amplitude and frequency of the detected peaks (which represent a vibrational mode of the pad) are clearly observable. This variation is the non-linear response of the structure at an imprecise excitation performed by hand.

With the novel SAM following parameters can be exactly controlled and adjusted between hammer tip and structure surface:
- The force amplitude level
- The exact impact point location
- The impact angle
- The impact time

This enables to excite precisely one “working point” on the non-linear spring curve. This procedure, measuring at only one operating point produces a valid measurement at one force level. If the material is non-linear, several different force levels can used to stitch a non-linear spring rate step by step together. The effect of controlled versus un-controlled measurements can be seen by comparing figures 2 and 3. Both figures show the same section of 10 FRFs at the same frequency spectrum. At the measurement in figure 3, the force input level could be kept constant with the assistance of the SAM. The eigenfrequency of the mode exhibits almost no variation, and thus, the non-linear behavior was eliminated of the measurement and a precise further data analysis was made possible.

Comparison with Existing solutions

There are several different commercial modal hammer concepts on the market. But the crucial precise control of the impact, in terms of contact time and force level is only in the SAM solution available. Furthermore the impact with the SAM is controllable in all directions in space. Due to the effect of non-linearity the precise controlled force adjustment is essential for any jointed structure or complex material. Furthermore it is important to have a precise, controllable and repeatable excitation point in terms of impact location, angle and time. In order to prevent damages on the surface of the tested objects, an exact setting of the force impulse is as well necessary.

For in field measurements in aircrafts, vehicles or constructed machines, the SAM is adjustable and can excite the structures with his stepper motor in all directions. Figure 8 shows other practical solutions of SAM and their properties in comparison with other solutions.
The SAM has a modular design and can be attached to different stands, to guarantee its precision and reproducibility qualities. It can be attached to a vertical Vernier scale (Fig. 9) or to a practical and flexible hydraulic arm magnetic stand (Fig 10, 11). Both stands are delivered with the SAM, and are of very easy use.

Possible Arrangements of the NV-TECH-Design SAM

The SAM was tested on a specially designed test plate before its release. The exact material characteristics and the exact dimensions of this plate are known and needed for an accurate simulation. The correlation of the obtained eigenfrequencies and results of the FEM is shown in figure 12 and the results of the cross-MAC matrix (Modal Assurance Criterion) are shown in figure 13.
Fig. 12: Correlation of the eigenfrequencies obtained through EMA and FEA of a test stainless steel plate.

Fig. 13: Cross-MAC (Modal Assurance Criterion) correlation matrix of the eigenfrequencies obtained through EMA and FEA of a test stainless steel plate.

Specifications of the Scalable Automatic Modal Hammer 1 (SAM1) from NV-TECH-Design

- Input voltage at the transformer: 230 VAC, 50 Hz
- Input voltage at the stepper: +24 V
- Current: 2 A
- Max. impulse force: 200 N
- Impulse force range: 10-200 N ± 4 N (*)
- Frequency range: 0 Hz ~ 20 kHz (*)

*) Values are dependent of the material properties of the tested structure.

Specifications of the Scalable Automatic Modal Hammer 2 (SAM2) from NV-TECH-Design

The large version of the SAM, called SAM2, is designed to excite and measure impact forces on small to medium structures. With this solution, it is possible to precisely test mid-sized structures such as gearboxes, engine blocks, alternators, generators or turbines and others.

Input voltage at the transformer: 230 VAC, 50 Hz
Input voltage at the stepper: +24 V
Current: 5 A
Max. impulse force: 2200 N
Impulse force range: 50-2000 N ± 4 N (*)
Documented frequency range: 100 Hz ~ 8 kHz (*)
Tested frequency range: 100 Hz ~ 12 kHz (*)

*) Values are dependent of the material properties of the tested structure.

The Company NV-TECH-Design

NV-TECH-Design was founded in 2015. The goal of NV-TECH-Design is to develop advanced, innovative NVH techniques for practical use from the laboratory through end of line test. The company owner has more than 25 years of practical NVH experience in leading positions at Robert Bosch GmbH and HEAD acoustics GmbH. Since 2010 he is professor at the TH-Wildau. NV-TECH-Design wants to establish itself as a start-up company with a core competence for NVH.