WaveHit$^{\text{MAX}}$: Sensor-based system for bounce-free impulse excitation of macroscopic solid structures

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Abstract

The following document describes the development of an improved smart impulse hammer for acoustic resonance analysis and experimental modal analysis. Starting with a detailed evaluation of the shortcomings of classical automated modal hammers, the development targets a substantial improvement of the existing problems with setup and operation in heterogeneous measurement environment. The result is a systems that significantly simplifies the impulsive excitation of various macroscopic solid structures.

Keywords: Impulse hammer, automated impulse hammer, modal analysis, acoustic resonance analysis

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1. Introduction

For a structural analytical investigation with the common instruments of vibration measurement, a defined and reproducible excitation of the investigated structure is essential. Beside the continuous excitation using electromechanical shakers, the impulsive excitation produced by impulse- or modal hammers is a common method. In its easiest form, the excitation is done manually using a hand guided hammer. When it comes to serial testing on a huge number of equal structures or the repeated excitation of a single structure (for example, at the roving sensor method), over the last years automated modal hammers became more and more important. Compared to a hand guided hammer they offer to opportunity to reproduce the excitation for an arbitrary number of hits in exactly the same way. Based on this, the reproducibility of the vibration measurement can be significantly increased. The automated impulse hammers currently available are basically semi-automated systems. These systems drives by replacing the human hand with an electromagnetic drive unit [1], [2]. Nevertheless these systems still needs a manual setup procedure to archive a clean single hit excitation. Furthermore they are not capable to compensate the lowest changes in the measurement setup.

Within the context of his dissertation, D. Herfert evaluates the whole tool chain used for vibration measurements and structural dynamic inspection using electromechanical sensors with the aim of simplifying the handling and minimizing the time requirement. Thereby he investigates research gaps related to the current methods of structural excitation preventing the formulated aim of simplification. He derived development targets and created a requirement document to be used as a foundation for future developments. Based on this work, the Engineering office for System Development and Software Engineering started in cooperation with the GFaI e.V. the development of an advanced impulse hammer which solves the identified problems from the ground.

2. Well known problems of automated impulse hammers

Automated impulse hammers are widely used in testing and measurement applications, where specimens needs to be repeatedly impulse excited in exactly the same way. The measurement setups can

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be very complex and they can include different types of devices such as sensors, data recorders, software and impulse hammers for the analysis of the test specimens. The time required for setup and iterative adjustments makes up a significant part of the total cost of such investigations. This also applies to the setup for excitation. Minimizing restrictions and better integration capability of the individual systems could significantly reduce the overall time and costs.

With regard to the previously mentioned (partially) automated impulse hammers, D. Herfert identifies the following obstacles:

- instability of the setup against tiny variations of the relative positioning of hammer and specimens
- missing fully automated setup process
- missing fully automated evaluation of the excitation, to verify of deny a single hit
- missing possibility of hand guided operation of an automated modal hammer
- missing possibility for the integration of a modal hammer in an automated test setup
- missing possibility to operate the hammer autonomously and retaining the full range of functions

Although all of the mentioned features offers an appropriate way to reduce the measurement effort of such systems, the first two are the most important ones. They directly affect the measurement quality. The mentioned intolerance against little changes of the relative position reduces the usability of automatic modal hammers in conjunction with series testing dramatically. Due to the automated transportation process e.g. by conveyor, there is usually a variable position of the specimen. Until now a dedicated manual adjustment of the automated modal hammer is necessary for each single specimen. This leads to a conflict with the claims of an automated testing process. But also for modal analysis, the need for a manual adjustment rises the handling complexity and increases the time and cost effort. Another disadvantage of partially automated modal hammers is the need for using a tripod or a comparable fixed mounting of the modal hammer. Hand-guided operations are not possible.

3. Concept and implementation

The first step in the development of a complete new fully automated impulse hammer was to investigate the existing solutions, especially their fundamental physics. All investigates systems share the concept of a impulsive excitation by the use of an electromechanical drive unit (a stepper motor in [2] and [3] or a solenoid driven tappet [1]) in conjunction with a moving mass which is mounted at the top of a piezo-electronic uniaxial force sensor. It is an important fact, that the drive parameters are static for each single excitation. Consequently the kinetic energy available for excitation is also fixed and has to be adjusted during an adjustment phase before starting the hit operation. Furthermore, the excitation of the specimen is performed by the utilization of properties of the mechanical components like the bending moment χ or a spring in case of a solenoid drive – see fig. 1.

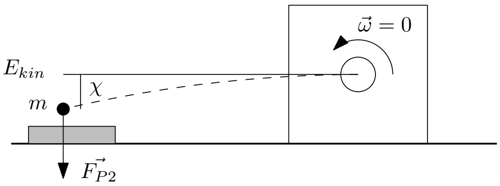

Figure 1: A classical (partially) automated modal hammer without a sensor-actuator control loop; The single hit is realized by the extensive use of mechanical properties like the bending moment of the arm.

This static manner of parameterization is the reason for the intolerance against little changes in the relative positioning of hammer tip and specimen, which results into length changes of the trajectory. The systems shares another common property by lacking a communication between the drive unit and the mounted sensor. The analog sensor signal is only feeded to an external connector and be recorded or analyzed externally. Thereby the automated hammer hits completely blind, it has no knowledge about the hit event. A true single hit excitation is only possible by adjusting the hammer manually for each single setup. Furthermore, this results into the requirement that the setup needs to be completely static in all its parameters during the whole duration of the measurement. Inevitable changes of the specimens surface as a result of the repeated impact of the sensors tip requires a readjustment of the system, because the effective length of the trajectory has changed. The set of hit parameter evaluated previously to achieve the wanted impact force are not valid anymore.

3.1. Implementing a sensor-actuator control loop

For the development of the fully automated impact hammer this problem was solved by implementing a closed control loop including the whole motion control – see fig. 2.

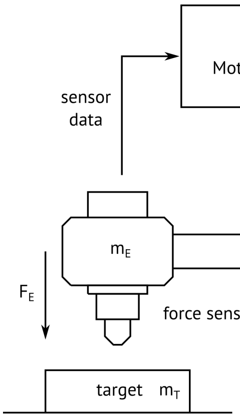

Figure 2: Schematic view of the sensor-actuator control loop for the internal motion control of the impulse hammer

The procedure of manually hammer in a nail was taken as a model. The human eye recognizes the positions of the nail (target) and the hammer (actuator) and especially their relative position. Additional information like the size of the nail or the mass of the hammer are also recognized by the kinaesthetic system, which helps to select the right hammer for the nail. To hammer in the nail, a reasonable amount of force is needed according to the material properties. A sequence of hits is done until the nail fits the wanted deep. During the whole process the acceleration of the hammer changes constantly, controlled by the human arm. When the hammer tip hits the nail, the moving direction of the hammer changes. Once again the reason for this is the information coming from the eyes and the kinaesthetic system. The system design of the new impulse hammer was modified so that the sensor signal acts as the main input parameter for the motion control unit. Doing so, the arm of the impulse hammer can be moved up to the hit point of the specimen, where the contact event is detected by a characteristic change in the force sensors signal and the moving direction of the arm can be inverted. The construction of the whole arm was modified in a way that the instrumentation can be changed by mounting different additional masses to match the needed mass relation between the moved mass of the arm mE and the resting mass mT of the specimen, so that it matches the relation $mE \ll mT$. Under this condition, the collision becomes an elastic characteristic. With the conservation of momentum

$$\sum \vec{p} = \sum \vec{p'}$$

it can be shown, that the implicit acceleration, induced by the difference of the masses in conjunction with the explicit acceleration of the arm by the drive unit makes a bouncing hit nearly impossible. A system equipped in such a way does not hit blind anymore. At the same time the system shown good stability against trajectory length changes, produced by changes of the position of hammer or specimen. A repeated readjustment of the specimen after small changes of the specimen position is not necessary anymore.

3.2. A fully automated adjustment

Due to the internal evaluation of the force sensor, there are extensive possibilities to improve the adjustment process. This step of preparation remains necessary, but can be fully automated and is done within seconds.

The adjustment procedure consists of two phases:

1. finding the impact point on the surface of the specimen
2. adjust the effective hit force to meet the users specification

Due to the fact that beside the amount of kinetic energy, also the effective force is determined by the selected instrumentation and the material properties of the specimen, an iterative automated procedure was selected, to find the settings that fulfills the specified hit characteristics within at most five test hits. If the user specifies the wanted impact force within a relatively wide min/max range and selects an appropriate instrumentation, the adjustment algorithm guaranties to find a solution in an arbitrary number of single hit excitations.

3.3. Automated hit quality evaluation

The existence of the sensor-actuator control-loop guarantees a single hit excitation.[1] Nevertheless

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[1] To produce a bouncing-hit we need to modify the measurement setup and utilize a very loose mounted specimen in conjunction with a violated mass relation $m_T \gg m_E$ between the mass of the specimen and the instrumented mass on the hammers tip.

the new impulse hammer implements an algorithm for hit quality evaluation. The evaluation is done in real-time subsequent to every impact event and consists of a qualitative and a quantitative analysis of the preceding hit. The qualitative analysis verifies the single hit characteristic of a excitation and returns the correspondent information to the user. The analysis process uses an algorithm which applies a kind of pattern matching to the recorded sensor signal. The existence or absence of characteristic attributes in the signal proofs or denies the single hit excitation. The quantitative analysis evaluates the time domain sensor signal compared to the signal sequence of an ideal hit. The deviation in similarity of these two signals is determined and immediately returned to the user as a relative scalar value – 0 dB (ideal hit), < 2dB (clean hit), < 3dB (sufficient hit quality). With the help of this value the user is able to determine the quality of every single excitation and furthermore his whole setup. Every deviation from an ideal hit is usually due to an inadequate measurement setup or instrumentation see fig.3. With the quantitative result analysis, the user can identify the source of the problem and correct his setup immediately.

3.4. Further integration and operational assistance

The key aspects described until here focused up to the stabilization of the primary system functions, especially the configurable, reproducible single hit operation. In general the identified obstacles listed above does not only contain functional aspects, but also non functional ones which makes it difficult to realize mostly seamless measuring setup.

None of the available (partially) automated modal hammers shares an open communication interface or an unified user interface. The signal provided by the internal force sensor is feeded to an analog voltage- or IEPE-output[2]. For any purposes of displaying or recording the signal, an appropriate system e.g. a data recorder or an oscilloscope is needed. Some systems are shipped together with a user software, that can evaluate the signal if it is provided to the audio interface of the computer.[3] In a rising number of cases today's computer lacks such an appropriate audio interface, which makes it necessary for the user to add it externally (i.e. an external USB device).

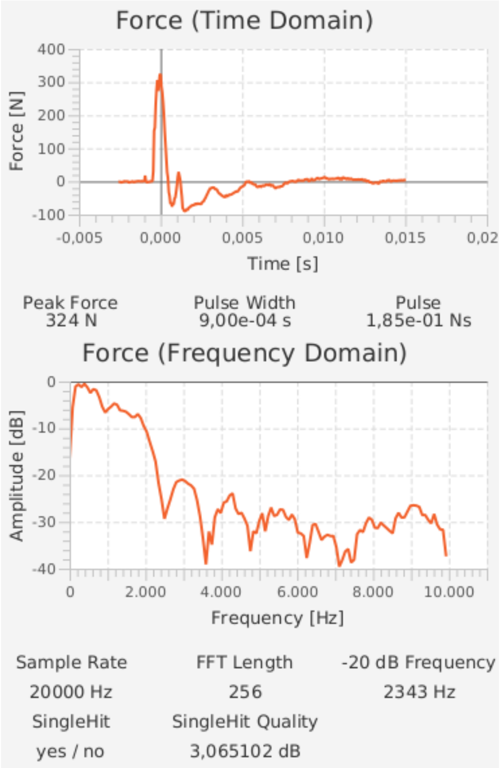

Figure 3: Signal plot of a non single hit Excitation; top: time domain signal, bottom: frequency domain signal

The operation of the (partially) automated modal hammer is done in reverse direction, a standardized interface does not exist. Up to today there are no digital interfaces for configuration and operation implemented. This makes the integration of such a hammer in an existing measurement setup difficult or even impossible. This problem is solved now by designing and implementing a common digital I/O interface, based on the Ethernet standard with a full TCP/IP stack on top. The communication on application level is realized by the interchange of JSON[4] objects, which are encapsulated in HTTP-POST requests. This provides the user with the full range of functions and all options for configuration and operation are available. Furthermore the sensor signals (time and frequency domain) recorded by the impulse hammer itself can be accessed selectively, as well as all the meta data of every single hit and the results of the hit quality analysis. The communica-

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[2] Integrated Electronics Piezo-Electric, a standardized interface for piezo-electric sensors

[3] When using automated modal hammers with a IEPE interface an external power supply with an integrated amplifier is needed to produce a voltage signal that can be provided to a computers audio interface.

[4] JavaScript Object Notation

tion protocols makes it easy to integrate the smart impulse hammer in his existing measurement setup.

Beside this, the impulse hammer does not need any external devices to operate. It can be completely operated in a self-sufficient manner. All functions for configuration and operation are made available to the user through the integrated HMI. Additionally the sensor signal is provided as a pure analog voltage signal.

4. Validation

The whole development process was accompanied by a continuous validation as part of the dissertation of D. Herfert. He used different practical measurement setups to verify single aspects of the new impulse hammer. He investigated:

- the single hit characteristics
- the characteristics of the impulses in conjunction with different kinds of instrumentation
- the fully automated hit point search
- the automated hit force adjustments

in all of defined possible variants of instrumentation. Specimens with different geometries and of different materials were used to increase the number of combinations.

Summing up the results it can be determined that the new smart impulse hammer satisfies the most of the functional development targets when it operates mounted on a tripod or guided by hand. When operating in series hit mode 95% of the measured effective hit force values are within the specified deviation interval. The maximum hit force was 2 kN with an excitation bandwidth of 12 kHz was observed when hitting on a steel car brake disc with an instrumented steel tip and an additional mass of 60 g.

It turned out that this combination of instrumentation and specimen (steel/steel) can be problematic, as the internal piezo element of the sensor tends to ring. This can lead to disturbance of the sensor signal.[5] Nevertheless the internal DSP algorithms are capable to do the qualitative and quantitative hit evaluation and can reliable distinct between ringing and a non single hit excitation. The validation of the automated hit force adjustment proved a deviation of at most 10% to the configured target force when operated from a tripod. When the hammer was hand guided, the deviation increased slightly. The number of test hits needed to archive the target force was 2 to 5.

The digital communication interface based on a HTTP/JSON protocol stack simplified the integration of the impulse hammer into the measurement setup significantly. In contrast to the existing (partially) automated modal hammers, the new impulse hammer offers a rich set of information for every single hit and combines it with semantic information. A direct comparison to other (partially) automated impulse hammers shows a reduced time and cost effort, which mostly comes from the tolerance of the system against little deviations in the measurement setup. This leads directly to dramatically reduced alignment and adjustment complexity of the whole system. The assist functions for automated alignment and force adjustment makes it easier for the user to bring the system up and shortens the time to the first measurement. The possibility for a self-sufficient operating mode makes it possible for the user to work without a additional computer for configuration and operation. The user is free to decide whether he want to use a computer without any restrictions in functional aspects. Thanks to the internal hit evaluation the user gets an instantaneous feedback about possible problems within his setup. There is no more uncertainty about the question whether a excitation was a single hit and if it was done according to the configured parameters.

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[5] The manufacturer of the used force sensor PCB Synotech GmbH advises to avoid this combination, because the piezoelectric element tends to ringing when excited by forces in the upper measurement range.

About the Authors

Andreas Lemke, M.Sc. studied computer science at the FernUniversität in Hagen and received the B.Sc. Degree in 2009. In 2018 he received the M.Sc. degree in Electronic- and Information technology from the FernUniversität in Hagen. From 2009 to 2014 he worked as scientific assistant for the Society for the Advancement of Applied of Computer Science (GFaI e.V.). In 2014 he started his own Engineering office for system development and software engineering. His focus is on development of custom specific systems for instrumentation and control engineering as well as power electronics and the construction of special systems.

Daniel Herfert, Dipl.-Inf. studied computer science at the Humboldt Universität zu Berlin and received his Diploma in 2010. From 2010 till 2012 he worked as scientific assistant for the Society for the Advancement of Applied of Computer Science (GFaI e.V.), research area Structural Dynamics / Pattern Recognition. Since 2013 he leads the research area for Structural Dynamics and Pattern Recognition of the GFaI e.V. His focus is on the software development, artificial intelligence, signal processing and structural dynamics.

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