A PC-based Flexible Solution for Virtual Instrumentation of a Multi-Purpose Test Bed

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Abstract—**The aim of the paper is to give an overview of a test bed set up for lightweight flexible structures. The purpose of the test bed is to compare different concepts for suppressing structural vibrations. It is demonstrated that such a complex measurement and actuation task can be easily implemented on a single PC using standard software like Matlab/SIMULINK® with a minimum of custom hardware. With the help of this PC standard engineering tasks like measuring, identification of transfer functions, as well as controller design and implementation in soft real-time can be carried out easily (rapid prototyping). The resulting system is flexible and scalable, enabling an engineer to perform all the above mentioned tasks for a given test object within minimum time. Additionally, the utilization of Matlab/SIMULINK® facilitates the realization of a versatile virtual instrumentation system which is easy to use and may also be remote-controlled.**

Index Terms— **Remote engineering, virtual instrumentation, rapid prototyping.**

I. INTRODUCTION

In the research and development of modern flexible structures the need for cost-efficient hardware and minimum time requirements for both setup and execution of measurements has led to a number of promising solutions. On the one hand, classical measurement and analysis devices such as oscilloscopes and spectrum analysers have become more intelligent by means of graphical interfaces and user specific function programming capabilities. On the other hand, computer systems for real-time applications have become more affordable, are equipped with user friendly interfaces, and can be applied to a wide variety of applications. Naturally, a classical trade-off between flexibility and complexity (which is closely related to costs) exists: One extreme are measuring devices built for a dedicated purpose, simple but rugged, operating in hard real-time, typically low-cost in pure hardware but affording a large amount of time for design and development. The other extreme is a standard PC equipped only with a minimum of input/output hardware and using a standard operating system thus only enabling soft real-time operation.

In the special application of a test bed for flexible structures clearly a very flexible solution for measurement and possibly control of the structure is sought for. This is obviously due to the need for efficient adaptation to different kinds of test structures, and another reason is that the diversity and complexity of available measurement and actuation devices used in technical applications have considerably increased over the last two decades. Therefore, simple, standardised, and low-cost components, a minimum of custom measurement hardware, and standard software programs are desired for the implementation of the measurement system. Furthermore, a standard PC may also be used for design and simulation of a control system, and this control system can be implemented on the same PC using either real-time operating systems or a soft real-time solution.

In this paper a test bed for a 1:10 scaled railway vehicle car body is described, which has been built to investigate different concepts to suppress structural vibrations by active damping. In contrast to pure measurement applications the implementation of closed loop control schemes requires both actuators with suitable amplifiers and a fast and versatile realization of the control unit. A software solution for a short development cycle from design to simulation and finally implementation of a control scheme is therefore necessary. Although different software packages for controller design and even more software solutions for simulation of closed-loop control exist, only few packages provide an integrated solution also covering the implementation of the control unit. In this case Matlab/SIMULINK® (http://www.mathworks.com/) running on a PC with Windows XP® has been chosen as software platform. This choice is based on the facts that

- A system identification for a given sensor/actuator configuration can be performed using the identification procedures provided within Matlab or custom programmed algorithms.

- Matlab offers extensive state-of-the-art control design toolboxes from conventional to non-linear and robust controller design.

- SIMULINK provides an easy to implement and well structured graphical user interface for implementation of the simulation.

- A close interaction between Matlab and SIMULINK allows for efficient interpretation and analysis of simulation results, therefore shortening the development cycle.

- The controller tested in a SIMULINK simulation can be directly implemented as a control unit.

- Closed-loop control can be performed either using the Windows Real-Time Target Toolbox (soft real-time under Windows XP operating system) or using the xPC Target Toolbox (hard

real-time with special operating system provided by the MathWorks).

In the remainder of the paper the construction and build up of the test bed, the measurement and actuation devices together with signal filtering and conditioning, as well as the software implementation in Matlab/SIMULINK® are described.

II. Test Bed

In Fig. 1 the test bed with the applied components is shown schematically. The test bed mainly consists of the test stand, the flexible structure of the scaled car body and all the components used for actuation and measurement (see Fig. 2).

The car body model is made from aluminium sheet metal which is adhered with a 2 component, structural metal adhesive and was designed with FE methods to exhibit dense lying eigenfrequencies. Some design aspects are given in [1]. Nevertheless, any flexible lightweight structure ranging between 1 and 2.5 meters and approximately 0.4 meters in diameter can be tested in this device.

The car body is suspended in the test bed by a defined elastic attachment between test stand and model via 4 coil-springs. The structure holding the springs can be adjusted in height using two handwheels. This construction allows a fine adjustment of a level structure as well as a comfortable and safe connection of the shaker. The shaker is mounted on an individual concrete foundation for the sake of vibration isolation. It is placed inside a heavy steel frame in order to enable different mounting positions relative to the structure. Utilizing this frame vertical as well as horizontal excitations can be applied to top and bottom of the structure, respectively.

The mounting position on the model is the relative position of the secondary damping elements of the real railway car. Using this suspension the model is mechanically comparable to a free running beam. In order to guarantee minimal disturbances caused by test stand-vibrations the springs have a very low natural frequency. In addition, the base-foundation consists of heavy steel-reinforced concrete plates. Welded steel profiles establish the basic structure of the test stand. All large or heavy elements are connected using bolt assemblies, therefore enabling a quick and efficient disassembling of the whole test bed. Each part of the test stand can be carried and handled by a single person. This type of connection adds also to the flexibility of the test stand, as adaptations can be made on the spot without using heavy gear.
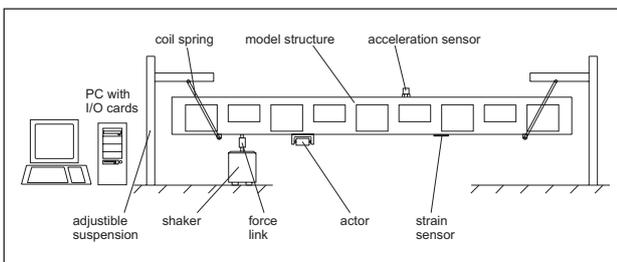

Figure 1. Sketch of the multi purpose test bed

Figure 2. Test bed bodywork in the laboratory

III. Measurement Equipment

A. Measurement Devices

In Figure 1 also the measurement and actuation devices are shown, respectively. Basically, three types of measurement devices are used. There is an acceleration sensor (Brüel & Kjaer 4383, piezoelectric charge accelerator, http://www.bkhome.com/), a force link (Kistler 9173B, SlimLine Quarz Force Link, http://www.kistler.com/), connecting shaker and structure, as well as two piezo electric strain type probes (SMART MATERIAL MFC M2814 P2, http://www.smart-material.com/). For the purpose of fault detection using hardware redundancy up to 7 strain sensors are used. In this case more narrow sensors (SMART MATERIAL MFC M2807 P2) are applied due to space requirements. All sensor types are based on voltage generation, proportional to the measured quantities, by the piezoelectric effect. The strain type probes are used for identification and control signal generation, respectively, whereas the actual performance variable to be controlled is the acceleration along the side members of the car body. However, the acceleration signal is not utilized as feedback signal since accelerometers are not desired in the real application due to costs. Finally, with the help of the force link the force actually transmitted from the shaker to the structure can be measured directly. This is useful for the identification tasks.

The usage of different sensor types also gives rise to the necessity of different measurement signal amplifiers and signal pre-processing, respectively. Therefore, charge amplifiers are used for acceleration and force signals, while the voltages produced by the strain elements are directly (not amplified) used as control signals. Nevertheless, in order to enhance signal quality by suppressing cross-talk between the channels differential amplifiers are used. A customized measurement system type MAS-10 which consists of a 19 inch rack housing contains the above mentioned charge amplifiers as well as signal pre-treatment devices such as the above mentioned low-pass-filters and differential amplifiers. As already mentioned in the introduction, this configuration keeps the need for customized measuring equipment to a minimum.

B. Actuation Devices

To simulate realistic vibration excitations generated by track irregularities a vibration exciter (Brüel & Kjaer 4809, Vibration Exciter) is used. Despite that there is only one but variable point of excitement all eigenmodes of interest can be excited (compare [1]).

For the implementation of different control concepts 2 piezo stack actuators (Piezomechanik, PSt 150/14/40 VS20, http://www.piezomechanik.com/) mounted in a specially designed console are used. The use of such consoles makes it possible to apply bending moments to the structure by using linear stack actors. These stack actuators can apply forces of up to 7 kilonewtons and a displacement of up to 80 micrometers. Accordingly, the bending moments generated by a stack actuator inside a console are much larger than those delivered by a patch actuator. The mounting of the actuator and the shape of the console together with some preliminary control results for a simple flexible beam structure are described in [2].

IV. SOFTWARE AND PC IMPLEMENTATION

Data-acquisition and -storage are carried out using only one PC with I/O hardware. The signals generated by the acceleration- and the force-probe are first filtered by a low-pass-filter (8th order Butterworth-filter with a cut-off frequency of either 800 hertz or 3 kilohertz) to suppress measurement noise and eliminate aliasing and then are passed on to the measurement card (NI PCI 6052E, http://www.ni.com/) implemented in the PC along with the strain measurements. These signals, which are proportional to strain, require no filtering but a differential amplification to be capable of eliminating interference which can easily occur using such high resistance sensor types.

Actuator signals e.g. for control purposes as well as excitation signals applied to the shaker are generated with the help of the measurement PC and fed to the according devices (high voltage amplifier type Piezomechanik LE 150/100) via an analogue output card (NI PCI 6703).

On the PC Windows XP® is installed, which is the basic operating system for Matlab/SIMULINK®, a standard application for technical engineering. Matlab/SIMULINK® is used for simulation and design of control systems, measurement, identification purposes and also real-time applications. In the presented case the Matlab/SIMULINK® Real-Time Windows Target Toolbox is used for control purposes that enable one to implement a soft real-time system easily and fast. Figure 3 shows a SIMULINK® model which was used for measurement, actuation, and control purpose.

An implementation with the help of the Real-Time Windows Target Toolbox is more convenient than an implementation in the xPC Target Toolbox (e.g. [3]), that enables one to achieve hard real-time. The main advantage of the xPC Target is the capability to run at much higher sampling rates or to use more involved control algorithms at a given sampling rate. Nonetheless, the compatibility of both available PCI cards makes it possible using the Real-Time Windows Target Toolbox as well as the xPC Target Toolbox, on the same PC. The requirement of an additional host PC for the xPC Target is not very restrictive since only minor hardware requirements have to be met by the host PC.

Using a PC equipped with a AMD Athlon 64 4000+ and 1GB of memory sampling rates of 6,667 kilohertz for identification and 4 kilohertz for control were easily achieved even with high-order controllers and observers.

With the so defined test bed rapid prototyping becomes very efficient. The central control is easily adaptable, scalable, and very fast to update. In a typical design cycle a new controller is designed using Matlab and a linear model identified from measurement data. Result of this design is a controller in standard LTI (linear time invariant) form, as well as theoretical predictions of the controller performance. Using a SIMULINK model this controller can be tested in a simulation where additional dynamics and non-linearities can be incorporated. Finally, the very same controller block from the simulation is inserted in a special SIMULINK model for control implementation (e.g. Fig.3), and after a short compilation the control loop can be started. As long as the controller structure (i.e. algorithm, order, number of inputs and outputs, respectively) remains unchanged the SIMULINK model needs no update. Only the controller parameters have to be changed, and all possibilities offered by SIMULINK can be applied.

Additionally, on-line data processing like filtering can be implemented in the SIMULINK model. Instead of building customized hardware or buying special devices, almost any purpose can be accomplished using a software implementation in SIMULINK. Existing block libraries can be used and the design of prototype filtering algorithms can be done more efficiently.

Post-processing of data (e.g. FFT) and storage can be carried out directly on the PC with the help of Matlab/SIMULINK®. Since data are directly stored on-line into the Matlab workspace, they are easily available for immediate processing right after an experiment has ended. The full functionality of Matlab can be exploited to get the most information out of measured data.

Thus, virtual instrumentation which considerably reduces the hardware requirements becomes easily and fast available. Furthermore, the whole test bed can be remote-controlled using standard interfaces like the OPC technology (http://www.opcfoundation.org) which is also supported by Matlab/SIMULINK.

Another advantage of the chosen system is its scalability regarding the number of necessary analogue input- and output-channels, which makes it possible to
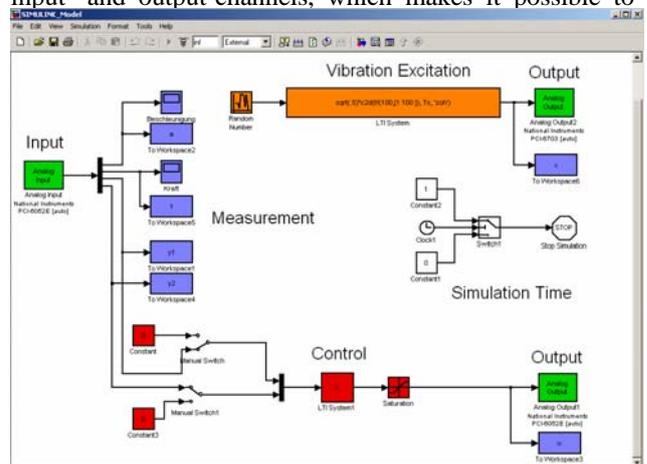

Figure 3. Simulink® model

connect all standardised measurement- and actuating devices. Currently, both cards provide in combination 16 single ended analogue input- and 18 analogue output-channels as well as further digital I/O´s which are not yet in use.

A. Practical Measurement

To execute measurements only a short initialization time is needed. Starting from an existing SIMULINK® model equipped with the appropriate input- and output-blocks, a building procedure – which automatically performs all the necessary interface connections - has to be carried out. After a short period of only several seconds all devices are ready to operate.

During operation some basic adjustments can be accomplished in "real-time", such as switching on (or of) a controller. Resulting effects can be seen instantly and also data recording is continuously performed during run time.

It is only necessary to rebuild the model if basic parameter changes or structure modifications need to be carried out. Parameter changes are especially simple and quick since the SIMULINK model need not be altered. But also structural changes in the controller can be done very fast once the controller design is done. The old controller block is simply replaced by the new one using a drag and draw technique.

B. Measurement on the car body

As an example measurement and control tasks carried out with the test bed are shown in Fig. 4. The depicted interface shows two scopes which enable the user to directly monitor current signals of interest. In Fig. 4 acceleration, as well as force measurements are shown. It should be mentioned that any signal can be monitored by a scope block regardless if directly measured or reconstructed inside the SIMULINK model. Several signals can be plotted simultaneously inside a single scope, numerical displays can be used, and user specific graphical interfaces can also be programmed.

Additionally, the inputs can be adjusted using the block structure that represents data acquisition and controller. These blocks are provided by the software manufacturer and can be parameterized using a window which contains all configuration parameters. This feature adds
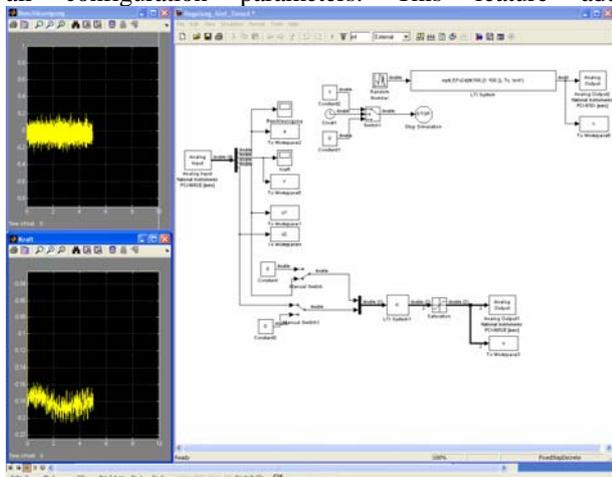
considerably to the easy scalability of the test bed. Whenever a new measurement or control output is augmented, the model's block diagram remains unchanged and only the parameterization of the individual blocks has to be adapted.

C. Signal Post Processing – Virtual Instrumentation

In Fig. 5 a typical time plot of an acceleration signal is shown. This plot has been generated subsequent to the measurement run in which signal data have been stored in the Matlab workspace. In such a way signal post processing like filtering, signal properties analysing and smoothing becomes easily available applying standard Matlab/SIMULINK® commands to the stored data sets. Thus, virtual instrumentation is realized which reduces the necessity for a large amount of measuring devices such as oscilloscopes, frequency analyzers and voltmeters. Fig. 6 additionally shows the Power Spectral Density (PSD) plot of the signal in Fig. 5 computed using the "psd"-command from Matlab/SIMULINK®.

Finally, it has to be remarked, that also remote engineering becomes easily possible for the described system when the PC is connected by a local network. For example, the experiment which has been built up in the laboratory can be driven by a remote PC somewhere in the
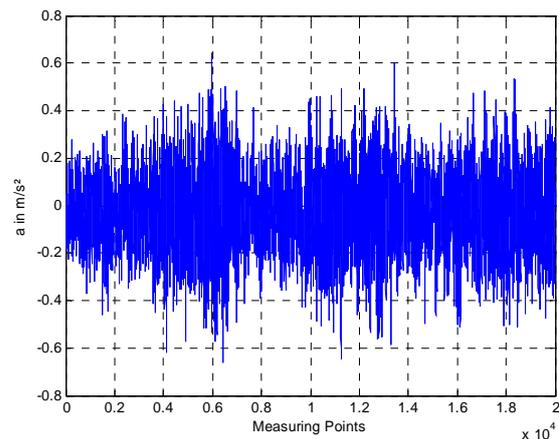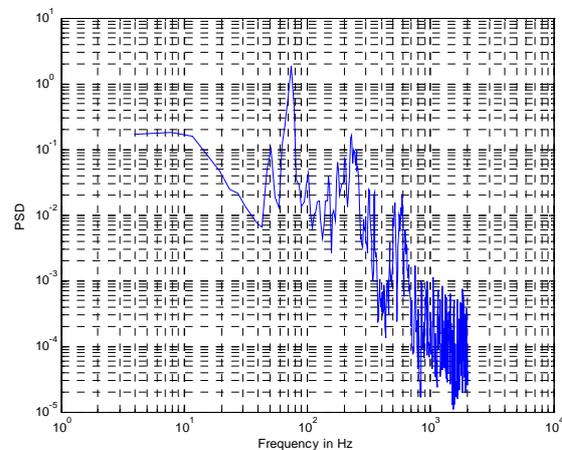

Figure 5.   Time domain, acceleration signal

Figure 6.   Frequency domain, PSD of an acceleration signal

Figure 4.   Online measurement and control of the car body

network connected via TCP/IP. In such a way data can be directly transferred form the test stand to any PC connected to the network. The above mentioned OPC server software is readily available in Matlab/SIMULINK® and facilitates this remote operation considerably.

V. Conclusion

A test bed for testing different active concepts to improve the structural behaviour of lightweight flexible structures has been presented. It consists of a modular test stand which can be easily adapted to a special test structure. In this paper the identification and active damping of a scaled model of a railway car body was investigated. Such a system comprises a large number of different measurement and analyzing-problems. All tasks from basic simulations and preliminary tests, to real measurements and signal pre-treatment can be performed with one system. The central measurement and control unit comprises only a minimum of custom components such as anti-aliasing filters and charge amplifiers. All other signal conditioning, computation of control outputs and post-processing of data are conducted using a single standard PC with standard software. Control tasks were performed in soft real-time on a Windows XP operating system. No additional instruments like oscilloscopes, signal analyzers or voltmeters have to be used.

Convenient operation with a minimum time for becoming acquainted with the test bed is possible if the user is accustomed in using Matlab/SIMULINK®. No further efforts such as programming of interfaces or long adaptation training have to be made. The described system is robust, easy to use and low-priced compared to other available customized measurement systems which often require a considerable amount of special hardware set up. The resulting system is not only easy to use, but it also offers the possibility to implement a remote operation via TCP/IP, thus enabling an engineer to perform test runs without the necessity of being personally present at the test bed.

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