Remote Experimental Vibration Analysis of Mechanical Structures over the Internet

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ABSTRACT

Experimental vibration analysis is of significant importance for e.g. the automobile and aircraft industry. It provides detailed information concerning the actual dynamic properties of vibration, structures, etc. Commonly, information from experimental vibration analysis is used in the development or modification of structures, processes, etc. to obtain for instance a required dynamic behaviour. It usually involves analysis methods such as; spectrum analysis, correlation analysis, experimental modal analysis and operating deflection shapes analysis (ODS). Large experience is generally required to obtain reliable results with these methods. The best way to acquire such experience is to spend many hours in a laboratory supervised by an expert teacher. However, in engineering education the experimental resources are limited and the traditional way of conducting vibration experiments is to participate in time limited scheduled lab sessions. Internet, however, provides the opportunity for engineering students to access the practical and theoretical knowledge advancement in experimental vibration analysis that is highly attractive for the industry. Laboratory exercises in, for example, experimental vibration analysis and signal processing courses, can now be performed remotely using real equipment. Advanced vibration experiments have been conducted over the Internet at Blekinge Institute of Technology, Sweden; the experiments have been carried out using experimental hardware located in a small closed laboratory. Exercises are adapted to on-campus students as well as distance learning engineers in continuing education programs. A new possibility to directly integrate vibration experiments into lectures given by expert teachers appears and after each lecture the students can repeat and elaborate on the experiments. Thus, enabling the students to carry out the experiments within a course at home using the time they require for sufficient comprehension. In this paper the remote experimental vibration analysis laboratory and its possibilities will be presented.

Introduction

Experimental vibration analysis has a central part in the development of cars, aircraft, etc. It provides detailed information concerning the actual dynamic properties of vibration, structures, etc. Information from experimental vibration analysis is generally used in the development or modification of structures, processes, etc. to obtain for instance a required dynamic behaviour. Modelling and prediction of dynamic behaviours of real physical systems, e.g. acoustic or mechanical systems, requires detailed knowledge concerning their actual dynamic properties. Experimental vibration analysis usually involves analysis methods such as; spectrum analysis, correlation analysis, experimental modal analysis and operating deflection shapes analysis (ODS).[1, 2] Measurements and subsequent analysis of vibration generally requires large experience to obtain accurate and reliable results. Experiments are thus fundamental for students in order to acquire the sufficient experience on measurements and analysis of sound and vibration.

The continuous expansion and development of Internet around the world opens for new possibilities for education to reach out to students. This infrastructure provides a new opportunity for engineering students to access practical and theoretical knowledge in experimental vibration analysis. This knowledge is highly attractive for industry, e.g. development engineers in the vehicle industry. For the industry it is fundamental to maintain their competence as well as gaining new knowledge for e.g. the engineering staff. Thus, the possibilities with distance education are likely to provide important opportunities also for the industry. Distance education reduces travelling time and cost as compared to a traditional education on universities distant from the working place and thus increases the efficiency of the time used to education. Hence, distance education is likely to be an advantageous choice for the industrial research workers.

A remote laboratory within the sound and vibration field is running at Blekinge Institute of Technology (BTH). The students have the possibility to perform the experiment at any time twenty-four hours a day, from anywhere in the world. Also other laboratories have been set up previously on BTH[3, 4] and also by other universities around the world.[5, 6] The remote laboratory at BTH is design to meet demands from both students on undergraduate educations and development engineers from industry, providing different tasks from basic to advance.

The experiment is designed to reflect on common a vibration problem in the manufacturing industry, i.e. vibration in metal cutting processes.[7, 8, 9] The object under investigation is a boring bar used for metal cutting in a lathe. Vibration problem associated with this type of process is considered to be an important and critical factor concerning the performance, the tool life, the surface finishing, etc. that finally ends up on the production cost negatively. Since it is shown that vibration problem originates from the lower order bending modes[7, 8] it is of most importance to examine the different properties of the boring bar i.e. finding the dominating bending modes.

Remote Experimental Vibration Analysis Laboratory

The remote laboratory consists of a client PC, a server PC, a signal analyzer, an amplifier, two accelerometers, an impedance head, an electrodynamic shaker and a experiment object. In figure 1 the remote experimental vibration analysis laboratory is illustrated. The server PC is the interface between the internet and the analyzer. The user controls all the settings necessary to perform the different tasks through an virtual instrument panel displayed on the client PC. The virtual panel is designed and implemented so it should look as similar to the real analyzer as possible; the students will then recognize the instrument and can handle it in the same way as in the traditional laboratory and vice versa. Also the conducting of the remote experiment it self is retained as similar to the procedure in the traditional laboratory.

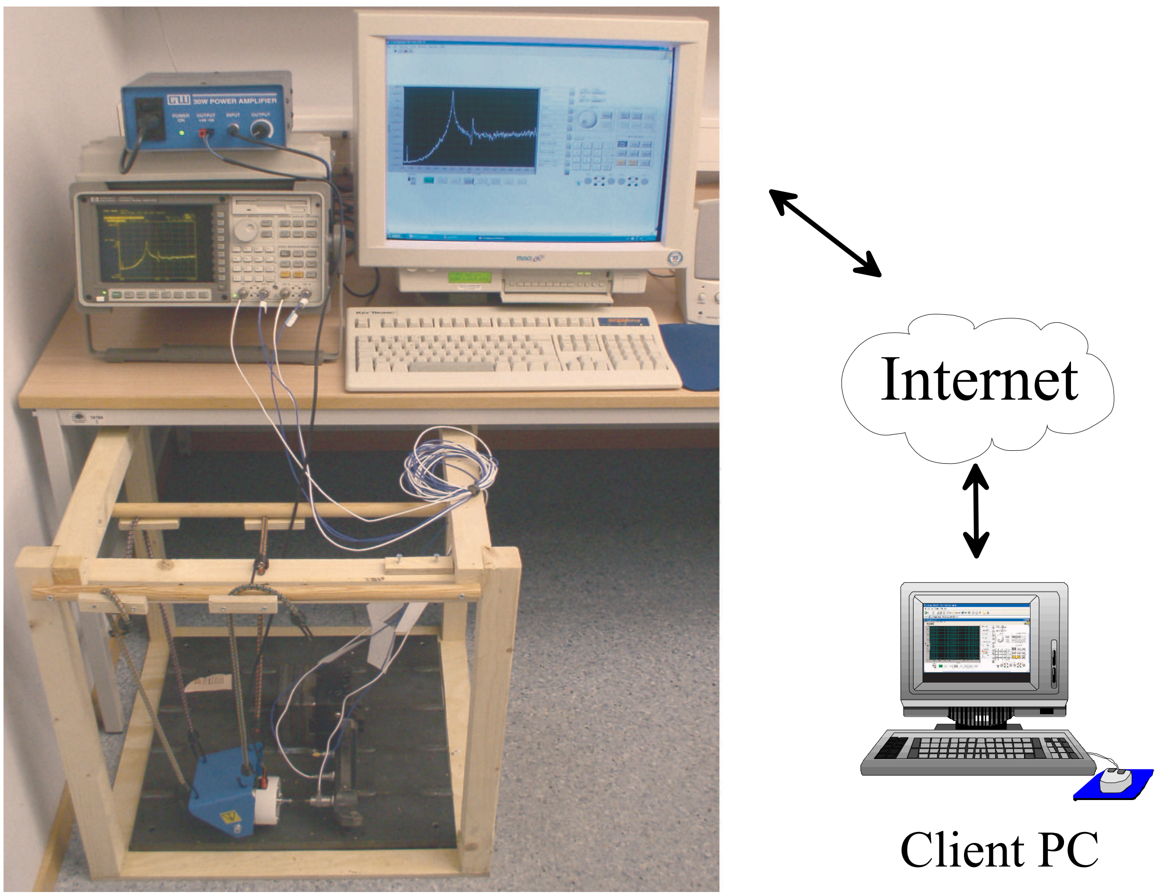

Figure 1. The remote experimental vibration analysis laboratory.

Client PC Virtual Front Panel

The front panel is programmed in Labview.[10] This program from National Instruments is widely used in the industry for controlling different instruments via Virtual Instruments

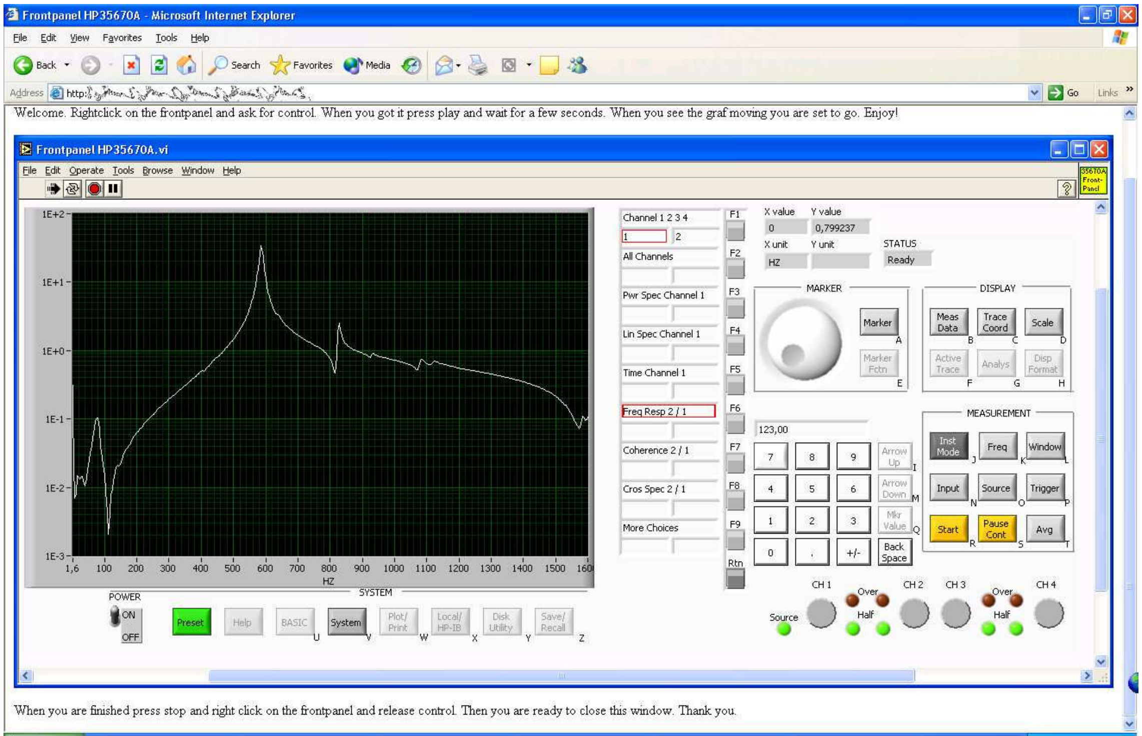

Figure 2. The virtual front panel of the signal analyzer loaded in a web-browser. This is what the client sees when using the remote laboratory.

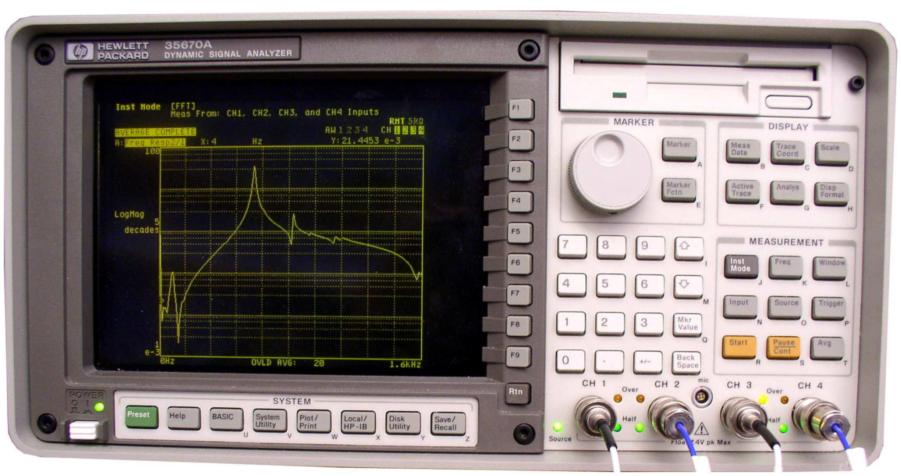

Figure 3. The front panel of the actual signal analyzer, this instrument is used by the students in both the remote laboratory and in the traditional laboratory.

(VI's). This program has many different features and one of them is the remote control panel which is used in this laboratory.[11] Labview is running as a server and provides internet users with a front panel in a form of a client able to control the instruments as easy as if the instrument was next to the user. When logging on to the web page to perform experiments the web browser will automatically run the remote instrument panel of the signal analyzer in same way as an java-applet is run. For this Labview needs an engine in same way as the applet needs a java-engine.

If this is not already installed the user is redirected to National Instruments home-page for downloading of the free LabVIEW Run-Time Engine. When the client is loaded, the user will see the front panel in the web-browser, see figure 2, which can be compared with real instrument, the signal analyzer, see figure 3. The user now has the control of the instrument and no other users are allowed to use the instrument. Besides the administrator of the server it is only the user of the signal analyzer who can release the control of it.

Server

The server consists of a number of different components (see figure 4): The HP35670A dynamic signal analyzer (see figure 3) is the main component in the server, it produce the excitation signal and collect as well as analyze the sampled version of the signals connected to its four inputs. The signal analyzer is connected to the PC server via a GP-IB interface and is controlled by Labview server. The analyzer source signal is amplified by an amplifier that powers an electrodynamic shaker. The shaker is mounted using four soft rubber strings, see figure 1, to avoid excitation of the structure under analysis via the shaker suspension. The shaker excites the structure under analysis via a slender stinger rod connected to the impedance head which is attached to the structure, i.e. the experiment object. The impedance head measure the force that is applied to the structure and the acceleration in the same point, i.e. the driving point. On the experiment object structure may also two additional accelerometers be attached at suitable positions.

A graphical user interface is provided in order to control the HP35670A signal analyzer over the Internet. The HP35670A signal analyzer has one source ”output” and four channels for measuring ”inputs”, which is sufficient to support adequate experiments. This instrument is familiar to the campus students from experiments in e.g. the undergraduate signal processing courses carried out in the traditional laboratory. Besides learning how the signal analyzer is working and how to collect, measure and analyze different data, the other important part is to understand how the shaker and the transducers works, such as impedance head and accelerometers.

The first part of the equipment in the measurement chain is the shaker, which produces a force analogous to the voltage over the shaker, next is the force transducer which converts the force to voltage. The force transducer is build in to the impedance-head together with an accelerometer which is the last transducer type converting acceleration to voltage, See figure 5 for the shaker and transducers used in the remote laboratory.

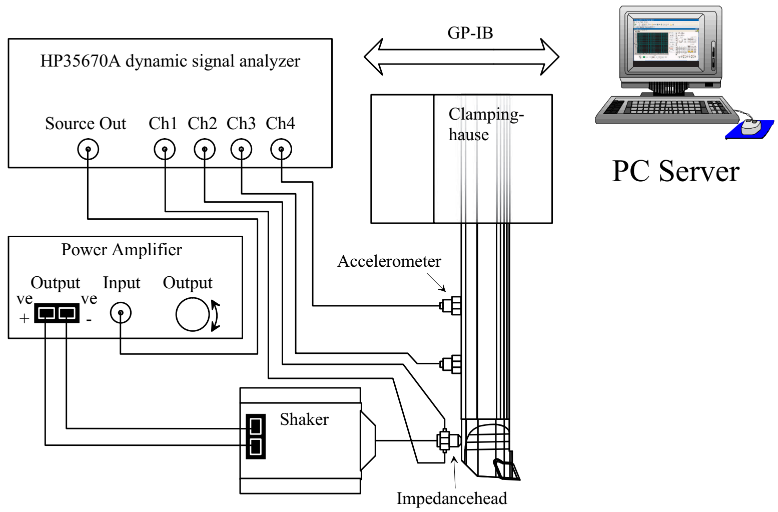

Figure 4. Block diagram of the server with a clamped boring bar as an example of experiment object structure.

The shaker is not an ideal force-source, i.e. the desired input force to a system is generally not applied to the system. This is due to the physical limitations of the shaker in a combination with the structure it is exciting. The stinger rod mounted between the shaker and the structure is applied to transmit force in the stinger rods axial direction while isolating shaker force perpendicular to its axial direction. The actual force applied to the structure is required e.g. in the system identification and experimental modal analysis supported by the signal analyzer and is measured by the force transducer in the impedance head. Finally the acclerometers are used for measuring the acceleration in different predefined positions in order to analyze the behaviour of the experiment object structure.

The Experiment Object

The central part of this Internet laboratory experiment is to analyze a boring bar, which is shown in figure 6. Boring bars are used in the industry for internal turning. The reason for designing laboratory experiments based on a boring bar is the easiness to understand the application in the industry as well as to realizing the complexity of the boring bar vibration problems. Internal turning is a typical example from the industry that generally is affected by vibration problems. In internal turning operations the boring bar is subjected to a stochastic excitation by the material deformation process.[7, 12] When the boring bar is used for internal boring in pipe-shaped work piece, the boring bar is usually shaped with a length that is much greater then its diameter (cross-sectional dimensions).[13] This shape of the boring bar results in a construction with low dynamic stiffness with respect to the excitation forces produced by the material deformation process. This results in large boring bar vibration amplitudes in turning. Vibrations during internal turning operations; reduce the surface quality on the work piece, reduce the tool life and generate acoustic noise, sometimes at unbearable levels.

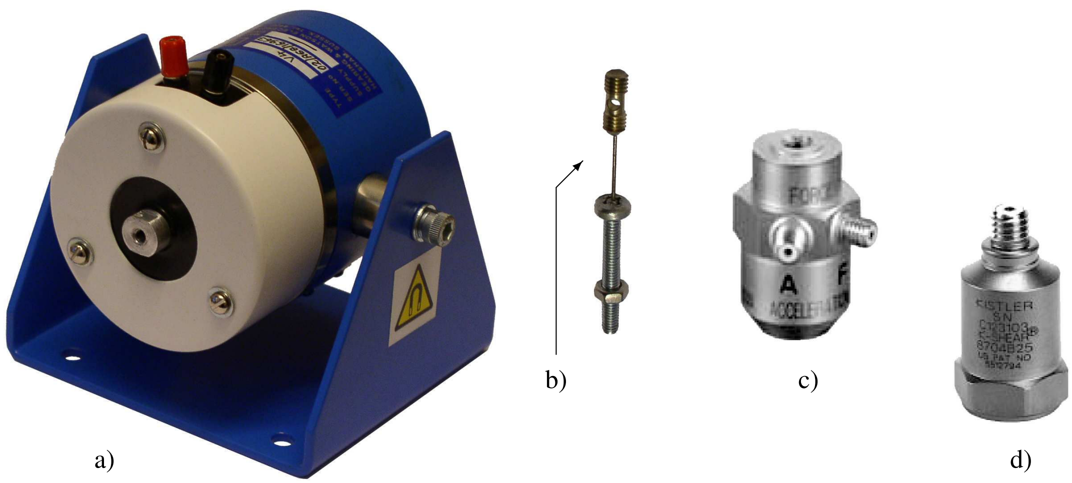

Figure 5. Equipment used in the experiment setup of the remote laboratory; a) The shaker for the production of exciting force to the boring bar. b) A stinger rod to ensure that the force from the shaker is only applied in the intended direction on the experiment object structure . c) The impedance-head for measuring both the force and the acceleration in the same point. d) The accelerometer for measuring the acceleration and there are two of those.

Figure 6. The boring bar used in the remote laboratory experiment setup.

The holder of the boring bar, clamping-house, see figure 7 is the first point of attachment for the experiment object. If the boring bar is not rigidly mounted in the holder, it will negatively affect the dynamic properties of the boring bar,[8, 14] i.e. the dynamics of the clamped boring bar may have sever non-linear properties. The boring bar is thus properly clamped using epoxy glue to join steel wedges in between the clamping house and the boring bar. The clamp bolts were subsequently tightened. The boring bar clamping is in its turn mounted with four bolts onto a homogenous and heavy steel construction, see figure 7. This is designed to simulate the real case when the boring bar and the holder is mounted in a CNC lathe. It is important to avoid flexibility in the mounting points, it can otherwise affect the measurements too much compared with the real case when the boring bar is mounted in a CNC lathe.

The Experiment

The shaker excites -according to the selected source signal on the signal analyzer- the boring bar experiment object via a slender stinger rod connected to the impedance head which is attached to the boring bar (see figure 7). The impedance head measure the force that is applied to the boring bar and the acceleration in the same point, i.e. the driving point. On the boring bar is also two additional accelerometers placed with some distance between each other. All four output signals, from the two accelerometers and the impedance head, are connected to the signal analyzers input channels, see figure 4. The boring bar is mounted in its holder as under normal conditions and the holder is rigidly attached onto a heavy steel construction in order to resemble the true case.

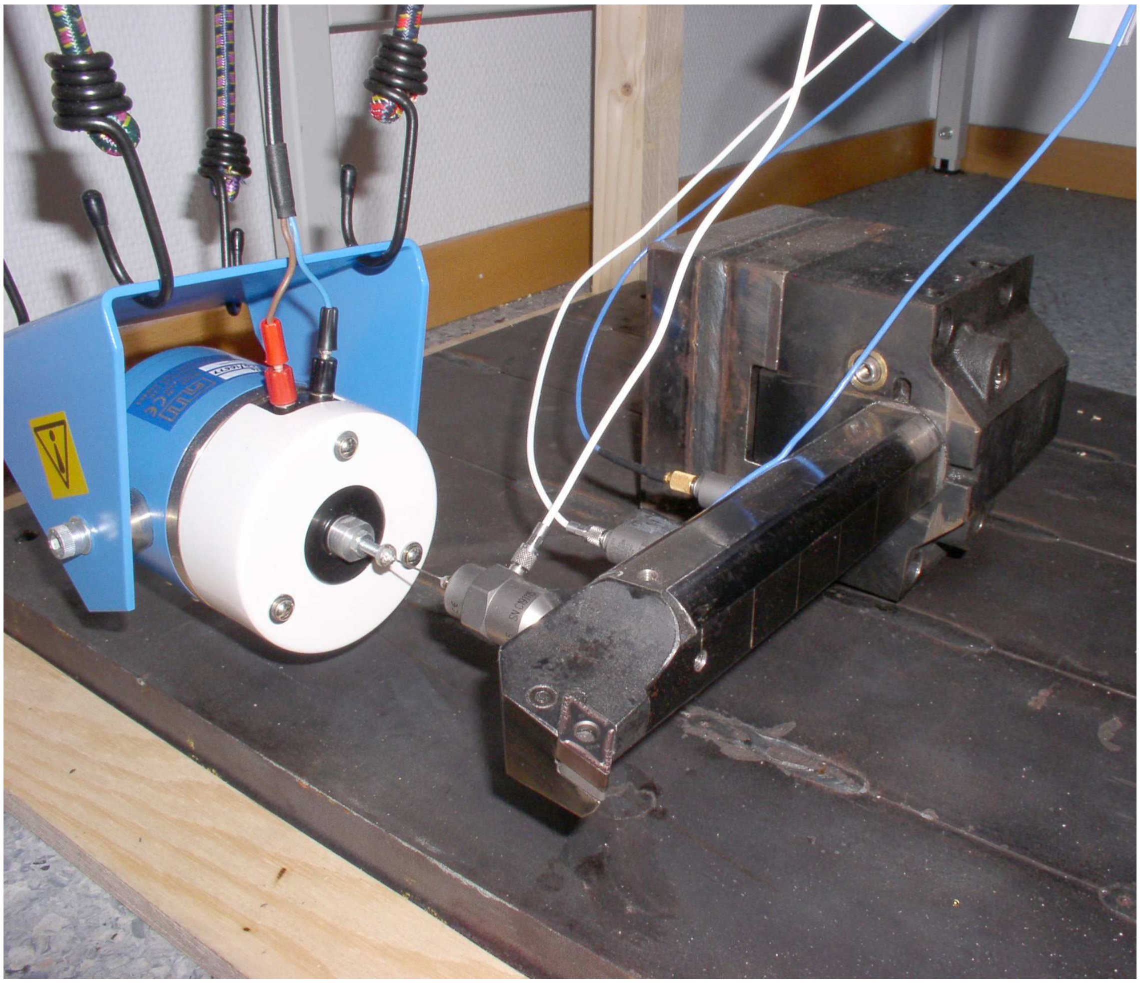

Figure 7. The actual experiment; the shaker coupled to the boring bar via stinger rod and impedance head and the transducers, accelerometers, mounted on the boring bar at the measurement-points.

Spectrum Analysis

To obtain statistically reliable frequency domain information concerning the phase and magnitude of the signals from the measurement points of an vibrating structure cross power spectrum estimates and power spectrum estimates may be used.[15, 1] In estimating spectral properties of a signal it is important to select an appropriate scaling of the spectrum estimator.[15, 1] The spectrum estimates may be scaled for either the tonal components of a signal -power spectrum (PS) estimates- or the random part of a signal -power spectral density (PSD) estimates-.[15]

(Auto) Power Spectral Density (PSD) could be seen as a special case of the cross power spectral density CSD, as the PSD is calculated based on one signal. The signal analyzer uses Welch's method for estimation of the single-sided PSD -the distribution of the total power of the response signals in terms of positive frequencies is produced[1]- with adjustable number of averages, adjustable overlapping, adjustable block length and selectable window. The Welch's method rely on the DFT (discrete Fourier transform) of e.g. the windowed sampled signal $w(n)x(n)$ whose PSD is to be estimated. The DFT of a windowed signal is produced by utilizing the FFT (fast Fourier transform) in the signal analyzer. The DFT of the windowed signal $w(n)x(n)$ is given by:

$$X_w(k) = \sum_{n=0}^{N-1} w(n)x(n)e^{j2\pi kn/N},\ 0 \le k \le N-1 \tag{1}$$

Where $x(n)$ is the signal to be analysed, N is the block length, k is the discrete normalized frequency and $w(n)$ is the window.

Expressed in terms of the DFT of the windowed signal $w(n)x(n+Nl),\ l \in \{1,\ \ldots, L\}$ the single-sided PSD estimate for the actual signal $x(t)$ without overlapping is produced as;

$$\hat{G}_{XX}(f_k) = \frac{2}{F_s LNU}\sum_{l=1}^{L} X_{w_l}(k)\, X^*_{w_l}(k)\,,\ f_k = \frac{k}{N}F_s,\ 1 \le k \le N/2.56 \tag{2}$$

$$\hat{G}_{XX}(f_k) = \frac{1}{F_s LNU}\sum_{l=1}^{L} X_{w_l}(k)\, X^*_{w_l}(k)\,,\ k = 0 \tag{3}$$

$$U = \frac{1}{N}\sum_{n=0}^{N-1} |w(n)|^2 \tag{4}$$

Where F_s is the sampling frequency, L is the number of averages, U is the window dependent compensation factor and the upper limit for the discrete frequencies in the analysis $N/2.56$ is introduced by the relation between the sampling frequency F_s and the cutoff frequency of the anti-aliasing filter used by the signal analyzer.

Integration of a single-sided PSD for the positive frequencies $f \in [0, F_s/2.56]$ gives the total power of the sampled signal. This means that the single-sided PSD can be used to estimat the power of random signals.

Welch's method uses averaging like Bartlett's[16, 17] method except that it also uses an overlap technique. By using overlapping, the number of effective data blocks may be increased. This, in turn, enables a significant reduction in the variance of the PSD estimate as compared to the case of no overlapping in the estimation of the PSD.[17] Depending on which window is used, different values exists for the amount of overlapping that yields optimal performance, i.e. minimal variance in the PSD estimate.

The Cross (Power) Spectral Density (CSD) is defined as;

$$\hat{G}_{YX}(f_k) = \frac{2}{F_s L N U} \sum_{l=1}^{L} Y_{w_l}(k)\, X_{w_l}^{*}(k)\,,\ 1 \leq k \leq N/2.56 \tag{5}$$

$$\hat{G}_{YX}(f_k) = \frac{1}{F_s L N U} \sum_{l=1}^{L} Y_{w_l}(k)\, X_{w_l}^{*}(k)\,,\ k = 0 \tag{6}$$

Single Input Single Output

There are different ways to carry out system identification when the input and output signals of the system is known. However, in real measurements these signals are always more or less contaminated with noise and this requires estimators that handle this problem. There are different methods that models different situations with respect to the noise. The first frequency response function estimator H_1 defined by Eq. (7) is applied in cases where it is assumed that noise only affects the system output, the second estimator H_2 defined by Eq. (8) is applied in cases where it is assumed that noise only influences the measured input signal. The third estimator H_3 defined by Eq. (9) produces the mean of the frequency response function estimates produced by the two previous estimators .[1]

$$\hat{H}_1(f_k) = \frac{\hat{G}_{yx}(f_k)}{\hat{G}_{xx}(f_k)} \tag{7}$$

$$\hat{H}_2(f_k) = \frac{\hat{G}_{yy}(f_k)}{\hat{G}_{xy}(f_k)} \tag{8}$$

$$\hat{H}_3(f_k) = \frac{\hat{H}_1(f_k) + \hat{H}_2(f_k)}{2} \tag{9}$$

Where $\hat{G}_{xx}(f_k)$ and $\hat{G}_{yy}(f_k)$ are the spectra of the input and output signals respectively. $\hat{G}_{xy}(f_k)$ and $\hat{G}_{yx}(f_k)$ are the cross spectrum of the input and output signals respectively However, it is reasonable to assume that noise affects both the measured input signal (force) and the measured output signal (acceleration). The problem of noise affecting both the measured input force and the output response signal may be reduced by using the H_c estimator.[18] This however requires that the input signal to the shaker is measured simultaneous with the force and acceleration response signal.

Modal Analysis

Modal analysis is defined as the process of characterizing the dynamic properties of a structure in terms of its modes of vibration. The experimental modal analysis is performed to either confirm an analytical finite element model or to characterize an unknown structure e.g. for troubleshooting. The process of characterizing a structure or system is called modal parameter estimating, also referred to as curve fitting. There are many methods for modal analysis with different advantages and complexities, e.g. peak picking and circle fitting.[19] The peak picking and circle fitting modal analysis methods rely on frequency response function (FRF) estimates, for extraction and determination of the modal parameter estimates for the structure under analysis.[19]

Experimental Modal Analysis

In the remote laboratory the goal of experiment is to extract the natural frequency, the relative damping and the mode shape for the low-order modes of the boring bar. By simultaneous measurements of the excitation force ”input signal” and the acceleration ”output signal” at discrete points of the boring bar defined by the sensor positions, frequency response function estimates may be produced between excitation force and corresponding acceleration responses using one of the previously mentioned frequency response function estimators.

Thus, experimental modal analysis of the boring bar in the cutting depth direction is enabled. The choice of excitation signal and driving point location influences the quality of the results from an experimental modal analysis. Excitation selection should be approached from the type of excitation signal desired and the type of exciter system available since they are interrelated. In this laboratory experiment an electrodynamic shaker is used to excite the boring bar. The best choice of excitation signal depends on several factors: available signal processing equipment, characteristics of the structure, general measurement considerations and, of course, the excitation system.[20]

Taking time to investigate preliminaries of the test, such as exciter or response locations, various types of excitation functions and different signal processing parameters will lead to higher quality measurements. Such preliminary checks are; adequate signal levels, minimum leakage measurements and linearity and reciprocity checks.

After the first measurement the driving point-FRF should be especially examined. When checking its imaginary part it should have all its resonance peaks in the same direction in the frequency area limited by the upper frequency limit of the subsequent modal analysis. If it is not so, then the impedance head is poorly mounted (the stiffness of the mounting is not sufficient).[2]

Summary and Conclusions

It is shown that it is fully possible to conduct vibration experiments over internet using a remote controlled signal analyzer with good results. As a result, the important opportunity for engineering students to access the practical and theoretical knowledge advancement in experimental vibration analysis is provided, which is also highly attractive for the industry. This also introduce a new possibility to directly integrate vibration experiments into lectures given by expert teachers and the students can after each lecture repeat and elaborate on the experiments. Thus, enabling the students to carry out the experiments within a course at home using the time they require for sufficient comprehension.

Because of e.g. firm fixing of all the transducers and the control of cables, this remote laboratory is likely to favorable concerning the quality of the measurements as compered to measurements carried out during lab sessions in the traditional laboratory.

Further implementation regarding scheduling of the access to the front panel has to be carried out in order to use this instrument in a larger scale. Also implementation of the unused functions on signal analyzer is necessary to get an apprehension of a complete instrument.

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BIOGRAPHY

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