Proceedings of the IMAC-XXVIII
February 1–4, 2010, Jacksonville, Florida USA

Impact Excitation Processing for Improved Frequency Response Quality

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NOMENCLATURE

ε	Small error
f	Frequency in Hz
Δf	Frequency increment (FFT resolution)
$\gamma^2(f)$	Coherence function

ABSTRACT

Impact excitation is the most common excitation type for measurements of frequency response functions for modal analysis and other purposes. The method used is almost always based on setting the data acquisition system up with triggering, fixed FFT analysis settings, and then using an accept/reject step where each impact is either accepted if the impact seems good, or rejected if it contained some error such as double impacts or overload. This method has several drawbacks that often lead to non-optimal frequency responses. In this paper, an improved method based on time recording of all signals and subsequent post processing is proposed. The data acquisition part is made easier with the proposed method, while at the same time the importance of a skilled operator is reduced. It is shown on a real test structure that the quality of the resulting frequency responses can be significantly improved (measured by the coherence function) compared to the traditional method, and at the same time the total acquisition time can be shortened. An automatic optimization procedure which allows for fully automated post processing is proposed.

1. INTRODUCTION

The way most vibration data acquisition systems are designed is based on the premises in the 1970's when the first FFT analyzers became available. One restriction in those days was the price of memory, and thus the way the data processing was implemented was to reduce data as soon as possible after acquisition. The result became the frequency block averaging that we use today and which is illustrated in Figure 1. The process waits for a trigger event and, when this is fulfilled, acquires a block of *N* samples into the buffer, which is then sent off to the FFT processor as soon as the buffer is full. Once the FFT process is completed, the data is sent to the averaging process where each frequency value of the latest FFT results is averaged into auto and cross spectra. Usually, for impact testing, there is an interrupt after the FFT process, so that, prior to including the new FFT results in the averaging process, the user can decide to include the new frequency results in the averaging process, or, if it was a bad impact, the user can decide to discard the data and make a new impact.

Several drawbacks of this technique are well known, for example that a relatively experienced operator is required for best results. The main reason for this, is that as the impacts are acquired and accepted into the averaging process, the end result is often dependent on the fact that all impacts are approximately equally large, and impacting the same location on the structure accurately. During the data acquisition, it is often also required to have one operator running the measurement system, accepting and rejecting each impact, and one operator working the impact hammer, although in some measurement systems there is an "auto reject" feature. From practical experience, though, we know that most of the time it is best to be two people for a good test.

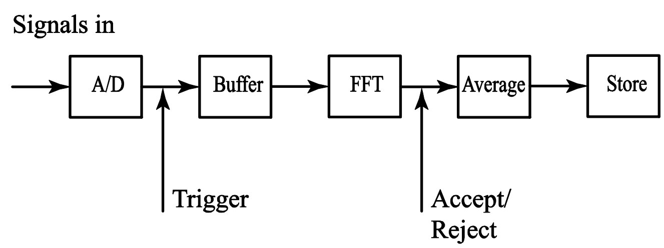

Figure 1. *Illustration of the data acquisition and FFT process involved in traditional impact testing.*

We assume that impact testing is rather well known. Details about the signal processing involved in the spectrum, frequency response (FRF) and coherence estimates can be found in e.g. [1].

2. IMPROVED METHOD

The improvement to the traditional way of performing an impact test which we propose in this paper is to replace the online averaging process by a separate recording of time data, followed by offline post processing to obtain frequency response and coherence. To evaluate the proposed method data were acquired on a slalom ski under free-free boundary conditions. The ski was instrumented with an accelerometer and an impact hammer was used to excite the ski in several locations, although only one measurement point will be presented here.

The method is very easy to implement and has been implemented in MATLAB. The main steps in the process are

1. Record a long time record with 5 to 10 impacts with enough time in between each impact
2. Find the impacts using a trigger level and apply a suitable number of samples pretrigger to make sure each impact is well defined in the time block
3. Apply a force window to the force, and exponential window to both force and acceleration
4. Select impacts to add for the averaging process by evaluating the coherence function as a quality estimator, only adding the impacts that give a good quality frequency response, i.e. one with a coherence function near unity.

The proposed method offers several advantages over the traditional way of performing impact testing. First, the measurement phase is considerably easier, since there is no accept/reject procedure involved, and no trigger conditions to set up. This is particularly important when the impact test is done for trouble shooting purposes in an operating environment. Second, the actual analysis process in steps 2. to 4. can be fully automated, and we will propose a simple yet powerful optimization algorithm to obtain high-quality frequency responses. In addition to these advantages there are several “side effects” which can prove to be important. The essential advantage is to have the entire recording as one, long time series. This allows for efficient signal processing such as removal of line power noise, and highpass filtering to remove rigid body vibrations, which can sometimes cause leakage effects when the structure is slowly oscillating on free-free supporting soft springs.

Impact testing involves a number of steps normally implemented in the measurement system. They include triggering, application of force and exponential window on each triggered time block, an FFT of each time block, and appropriate averaging to auto and cross spectra which are finally combined into either an H_1 or an H_2 estimate of the frequency response. As the noise in the force sensor can usually be almost entirely removed by the force window, the H_1 estimator which minimizes noise on the output (accelerometer) is generally the best estimator.

```
xM=max(abs(x));          % Max peak in x (force signal)
TL=TrigPerc*xM/100;      % Trigger level in units of x
x(end)=xM;               % To make diff work without losing last impact
dx=diff(sign(x-TL));     % Distance between trigger points
TrigIdx=find(dx > 1);    % dx has a value of 2 where there is a trigger
```

Figure 2. *MATLAB code to find the trigger locations on the force signal in vector x. The code works for positive peaks and positive slope.*

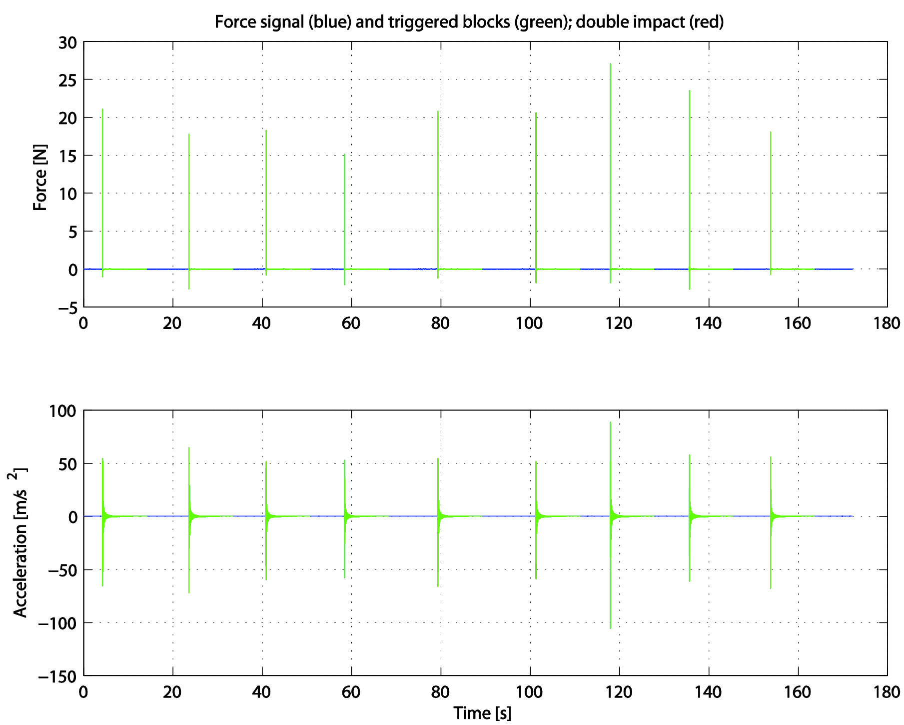

Figure 3. *Plot showing the force signal (upper) and response signal (lower). The entire signal is plotted in blue, and each defined block from the trigger point and N consecutive samples is plotted in green.*

The first step in the post processing is to find the impact occasions. This is done in MATLAB very simply by a few short lines of code as shown in Figure 2. The data is in the vector denoted x, and the trigger level is given as a percentage of the maximum impact peak.

After the trigger events are found, the indices should be subtracted by the number of pretrigger samples one wants, so that the beginning of each force impact is well inside the data block. In Figure 3 a plot is shown where each block of data (using a preselected blocksize, see more below) is marked in green, plotted on top of the entire time data series in blue. It is easy to implement a double impact detection and for example plotting the blocks which contain a double impact in red in a plot similar to the one in Figure 3. This has been implemented but we omit it here for simplicity.

After each impact and response block are thus defined, appropriate frequency analysis settings should be evaluated. This is another great advantage with the proposed method, as we can now very easily analyze the data in Figure 3 over and over again with different blocksize, force window parameters, and exponential window parameters. The only limitation is that we can only use blocksizes that make each block well defined, i.e. the blocks may not be so long as to go into the next impact. When estimating frequency responses, the frequency increment must be sufficiently small so that the bias error that comes from the discrete approximation of the continuous frequency response becomes negligible. This should be investigated by calculating the frequency response with successively decreasing frequency increment (i.e. increasing blocksize) until two consecutive blocksizes show approximately the same peak height at the first resonance (assuming same damping for all modes). The blocksize can then be set to the lower of the two.

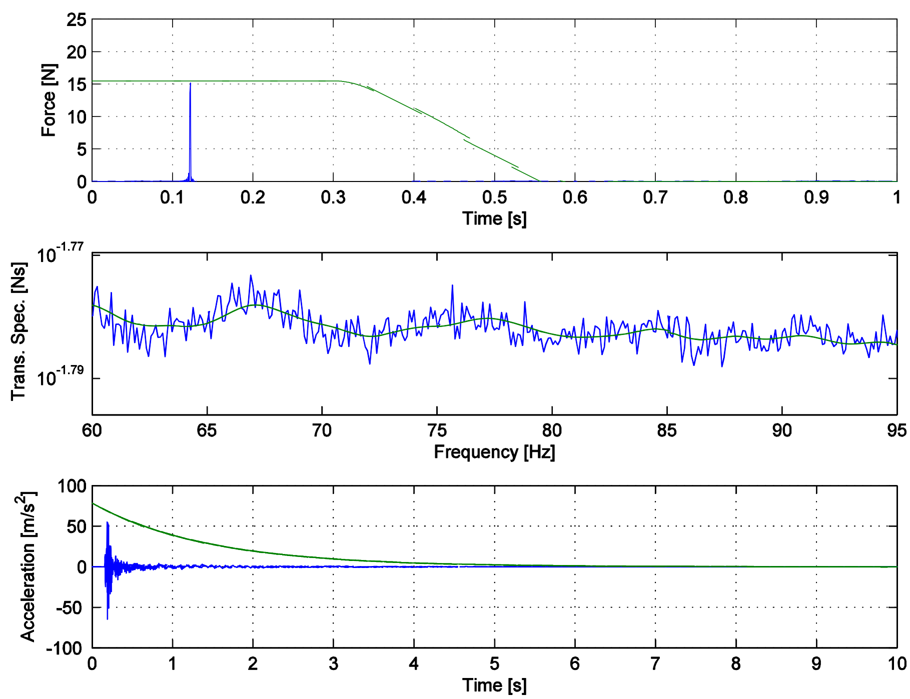

Figure 4. *Plot showing the force signal (upper) overlaid with the force window, and the spectra of the unwindowed and windowed force signals (middle), and a response signal and exponential window (lower). Note that the upper two plots are highly zoomed in time and frequency, respectively. Also, the force windowed has a scaling to fit the plot, its actual values are of course 1 over the flat part. A scaling has also been applied to the exponential window, which in reality starts at one for time zero.*

Once an appropriate block size is selected, the force window should be optimized. A good force window can be defined by a certain length with unity values, followed by a half period of a cosine with approximately the same duration. In Figure 4 (top) one impact force is plotted together with the force window chosen for the example later in this paper. The force window removes the noise in the force spectrum (middle plot) almost entirely.

The final step in the frequency settings stage is to optimize the exponential window. This can be done by applying a successively stronger exponential window until no apparent improvement is seen in the coherence. It should be noted especially that it is important not to forget to add the exponential window also to the force signal, as the increased damping effect can otherwise not be properly compensated for, [2] if the frequency response is to be analyzed for damping (for example through modal analysis curve fitting).

3. OPTIMIZING FRF QUALITY

As can be seen in Figure 3 there is some discrepancy between the force levels of each impact. This illustrates how difficult it is to perform identical impacts with a common impulse hammer. On a slightly nonlinear structure (as many structures, if not all, are) this will result in a badly estimated frequency response. However, as we are post processing data, we can very easily decide to choose only impacts with approximately the same force level. In Figure 5 a plot is shown of frequency response and coherence where the first five impacts have been used. As is seen in the plot the quality is good (coherence of unity) at most frequencies, with an area between approximately 70 and 90 Hz where, at the deep antiresonance region of the FRF, the coherence drops, indicating a low signal-to-noise ratio. At approximately 75 Hz there is a resonance which coincides with a dip in the coherence, a most unwanted situation.

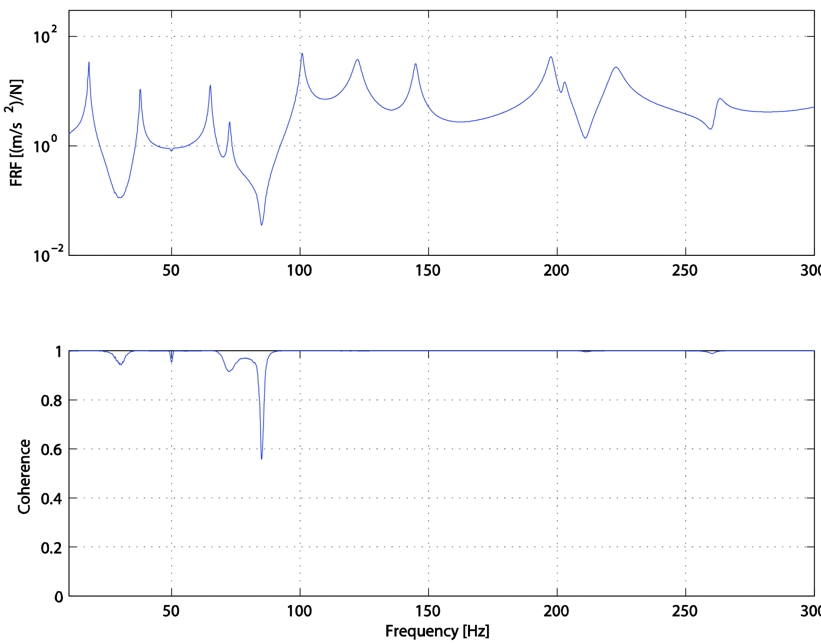

Figure 5. *Plot showing a frequency response (upper) and the corresponding coherence function. The first five impacts of the time series in Figure 3 have been used in the averaging process to compute both functions.The result corresponds with what one would expect from a measurement using the traditional impact testing process.*

Note that the results in Figure 5 is what one would expect as the result from a traditional averaging process for impact testing, as none of the five impacts used showed any apparent signs of problems. In order to possibly find a better estimate of the FRF, a simple optimization algorithm was developed. To limit the computational time, first all pair combinations of two out of the (in our example) 10 impacts are used to compute the coherence. The pair is chosen which minimize the error function ε, defined by

$$\varepsilon = \Delta f \sum_k \left(1 - \gamma_k^2\right) \tag{1}$$

where γ_k^2 is the coherence function for discrete frequency value *k* corresponding to frequency $f = k\Delta f$, and $\Delta f = f_s / N$ is the frequency increment, using a sampling frequency f_s and blocksize of *N* samples. A frequency region of interest is chosen and used for the error calculation. After the first two impacts have been chosen, each of the remaining impacts is added individually, the coherence function is calculated, and for each impact the error function defined in Equation 1 is calculated. Those impacts that reduce the error function are added to the averaging process.

The result of applying the optimization algorithm is shown in Figure 6. As is seen in the figure, the coherence function is substantially improved, and thus the FRF quality. Only a narrow dip remains at the strong antiresonance of the FRF.

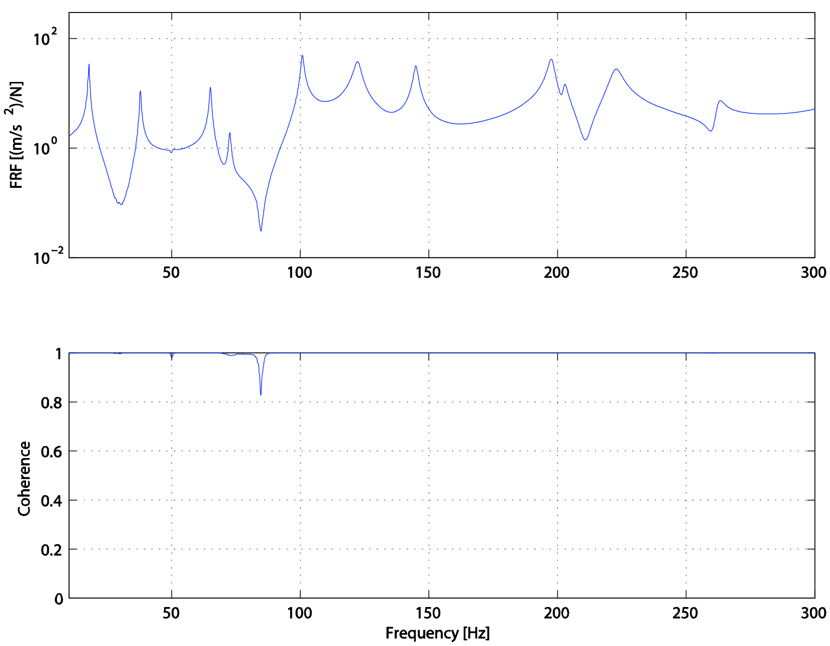

Figure 6. *Plot showing a frequency response (upper) and the corresponding coherence function for the optimally chosen impacts. The problem area in the frequency range 70 to 90 Hz is considerably improved compared to using the five impacts that produces the FRF and coherence in Figure 5.*

CONCLUSIONS

We have proposed a modified method for impact hammer excitation and shown on example data that the method can improve the quality of estimated frequency responses. It is based on time recording of a number of impacts and responses into a file, and subsequent post processing. An optimization algorithm to automatically select impacts for best FRF estimate was presented. The method has a number of advantages, such as

- Easier data acquisition because the operator only needs to make impacts, and not have any interaction with the measurement system during the data acquisition.
- Less importance of an experienced impact hammer operator, as impacts of equal force level can easily be selected in the post processing stage.
- Improved means of optimizing frequency analysis settings as no new measurement is needed after each change.
- Better coherence can be more easily and reliably obtained by choosing only impacts that give a better coherence function (FRF quality).
- Easier to apply signal processing to remove 50/60 Hz line frequency noise and highpass filtering to remove effects of low frequency oscillations on soft springs support of the structure.

REFERENCES

[1] Bendat, J. and Piersol, A. (2000), *Random Data: Analysis and Measurement Procedures*, Wiley Interscience.

[2] Fladung, W. & Rost, R. “Application and correction of the exponential window for frequency response functions,” Mechanical Systems And Signal Processing, 1997, (11), p. 23-36.