MIMO RANDOM CONTROL METHOD FOR VIBRATION TESTING

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Summary

In following paper control algorithms used for MIMO vibration control were presented and investigated with regard to application in modal analysis. Implementation of existing control algorithms was presented for verification of its operation and development of new method combining several older methods. Objective of implementation of new method was increasing performance and quality of calculations and closer look in to development of SINE SWEEP and TIME WAVEFOR REPLICATION. Comparison of simulation and measurement data is presented in two cases of control with six degree of freedom system.

Keywords: modal analysis, vibration control, environmental testing.

ROZWÓJ SYSTEMÓW STEROWANIA DLA TESTÓW WIBRACYJNYCH MIMO

Streszczenie

W artykule opisano istniejące metody sterowania MIMO, oraz ich zastosowanie w analizie modalnej. Przedstawiono implementację istniejących algorytmów sterowania do testów wibracyjnych MIMO celem weryfikacji ich działania oraz połączenia ich w nową metodę sterowania. Celem utworzenia nowej metody sterowania było zwiększenie wydajności i jakości obliczeń a także spojrzenie w kierunku dalszego rozwoju sterowania do metod SINE SWEEP oraz TIME WAVEFORM REPLICATION. Porównanie wyników symulacji oraz danych pomiarowych zaprezentowane jest na dwóch przykładach kontroli systemu o sześciu stopniach swobody.

Słowa kluczowe: analiza modalna, sterowanie wibracjami, testy środowiskowe.

1. INTRODUCTION

1.1. Purpose and resources

Most of the research and calculations presented in following paper were performed as a part of internship project in LMS International, in Belgium. The project was related to verification and development of control algorithm used in part of software that is produced by the company. Main purpose of the research is controlling vibration environmental testing of structures requiring multiple points of excitation. The research is based on various control methods applied for vibrational testing starting from elongated structures random control through sine control and finishing on square system models.

For better understanding the principle of vibration testing that will be discussed in details, it would be roughly described on an example of structure that could be observed in everyday life, for example car dashboard. Dashboard – which in further description would be called test subject is analyzed in normal operation conditions. Multiple accelerometers are placed on the test subject and road test is conducted. Therefore stored data from accelerometers is a target result that is desired as a response in environmental test (either spectrum of data – random control, or time signal – time waveform replication). For this purpose algorithms listed before are used in processing the data and creating drive signals for exciters that are connected to test subject. Exciters have got to be controlled in this way that response signal of accelerometers mounted on test subject match in given threshold the data from road test or other assumed form.

1.2. Description of problem

Starting with sketching up main principles of MIMO testing would be most convenient to describe what exactly is happening with the system and how it is done. As presented in previous part of introduction, test that is performed is done on some mechanical structure, which is either suspended or mounted on shaker system (TEAM Cube device). Structure is excited with vibrations. Basically exciters (electrical, hydraulic etc.) are acting on the structure with force that is variable in time. In case of MIMO analysis, the number of shakers must be higher than one. Currently tests were done with up to 6 exciters.

When structure is being excited by means described above, response of the system is measured by multiple accelerometers. In current stage the whole setup is prepared to process square systems – those consisting of same number of inputs and same number of outputs. Means used for digitalization of results are SCADAS, which front ends are also used for creating drive signals for exciters. Front end is connected to amplifiers of given type of actuation, either for electromagnetic shakers or hydraulic valves.

Data acquired from measurements is processed in computer software Test.Lab, for which algorithms are being developed. At first part of the measurement so called system identification is performed, which basically is exciting the system with band limited white noise. Usually the band of the noise is much wider then band in which test itself is performed.

2. DESCRIPTION OF MEASUREMENT SETUP

For executing operations for which calculations are performed in control algorithms, proper hardware is needed. Measurement and actuation devices along with data acquisition systems are considered to be a part of system under test. First device that would be described is double function device, used for creating time signal that is sent to amplifiers and is used also for collecting data from transducer. This device is called SCADA. In research performed in company various types of data acquisition systems were used, all of them where compliant with Test.Lab software. Devices are also produced by the LMS International Company.

For converting drive signals to force actually exciting the structure, various types of shakers where used, for electrical shakers amplification of signal was required. For creating the analog signal from values computed by the algorithm, digital to analog converter is used. In case of hydraulic shakers systems with PID controllers controlling valves that are responsible for driving actuators with given form of signal were required.

As a final piece of equipment connected back to SCADA, transducers modifying accelerations in to electrical signal which then is processed through analog to digital converter, and further processed as a digitalized value in the algorithm itself.

2.1. Measurement and signal generation

Supervisory control and data acquisition systems are devices used for gathering and processing data. Usually the devices are converting electrical values such as voltage to digital form that can be processed further by computer. Second application of SCADA systems is generation of analog signal, that could be further directed to devices that are being controlled. For processing input data, subsystems called Analog to Digital Converters are used, principle of operation of this type of subsystem will be discussed in further parts of paper, along with devices for output signal generation, Digital to Analog Converters.

Those devices are available in various sizes and configurations, following from mobile devices with rugged construction to multiple customizable systems with interchangeable cards. Following devices are able to provide from 8 channels up to 2000 channels when connected in network. In many types of data acquisition and control systems wireless communication is embedded for various diagnostic and test applications.

2.2 Excitation system

Exciter is a device which role is to excite vibrations in the structure. Sometimes it is called shaker. Simplest way of describing this device is, to say it's actuator with very small amplitude of motion. We can diversify exciters in three main groups: electrodynamics, piezoelectric and hydraulic. Those types of exciters have various applications usually regarding size of the structure, amplitude and bandwidth of desired vibrations

Perfect example of multi axial hydraulic exciter system is device called Cube, produced by TEAM corporations. This unit is composed of six hydraulic shakers mounted inside of cubic structure which outer surface is prepared for mounting test pieces for measurements.

Each of the exciters composing this device is responsible for one degree of freedom in motion that is executed by the device. According to the manufacturer the device operating frequencies range from 0 to 250 Hz, can provide displacement of 100mm and force up to 62 kN.

TEAM cube was used for testing MIMO random algorithm mentioned in literature, results from measurements and tests where used in Matlab validation discussed in details in further parts of the paper.

Figure 1. Team CUBE in KU Leuven

2.3. Sensors

Devices that are used for gathering information about vibrations – transducers converting values of acceleration to electrical signal are called accelerometers. There are many types of accelerometers that vary regarding on the principle of operation. Currently most common type of accelerometers that are applied for research and test applications are MEMS accelerometers. MEM stands for Micro Electro Mechanical System. But the first and most groundbreaking device that was introduced was piezoelectric accelerometer. Piezoelectric accelerometers mostly find application in commercial use rather than testing. MEMS accelerometers are usually small systems, in many cases 3 accelerometers in one device – oriented along 3 axes. These type of accelerometer are called 3 axis accelerometers and provide data about motion in 3 dimensions. Principle of operation of MEMS accelerometers is based on cantilever beam with seismic mass attached to it. Due to the motion of the device, mass deflects from its original position. Deflection of the mass is measured, in most cases in analogue way, converting the deflection to capacitance – due to change of distance between two conductors. Than the capacitance has an influence on the voltage that is between two parts of the material and is further processed in SCADAS system connected via shielded cable to the accelerometer. Biggest disadvantage of using this type of devices for measurements, is introducing their mass to the system, what causes changes in the system properties.

3. THEORETICAL BASE FOR ALGORITHM DEVELOPMENT

3.1. Control method

First step that was performed during research regarding MIMO random was implementation of system identification of TEAM Cube (6 exciters - in description called “Output 1, 2, …, 6”) equipped with 12 response channels (accelerometers) placed in corners of the cube (1, 2, 3, 4) at the top and bottom side, measuring acceleration in X, Y or Z, to old existing algorithm, that was used and developed for testing elongated structures such as pipes and elongated boxes.

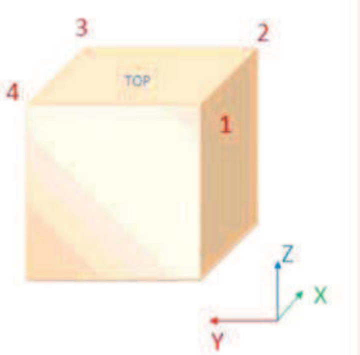


Figure 2. orientation scheme of CUBE

During data processing in this algorithm data taken from system identification is being interpolated so that FRF could be used for creating longer time domain signals that are being used for simulating drives.

Frequency response model is showing relation between inputs and outputs as Amplitude [(m/s2)/V] vs. Frequency [Hz]. System identification was performed in much wider spectrum than shown on plots, but only band from 20 to 200Hz was chosen for simulation and environmental testing, due to the characteristics of the system.

After implementation of FRF the reference model was implemented. Two tests were performed with two reference models, for which Cross Spectral Density, Power Spectral Density and Coherence was adjusted in the way giving two easily observable schemes of structure behavior. 1st example was “Zrotation”, so control algorithm had to adjust the input signals (drive signals) in such manner that the Cube would only execute vibrations as rotation around Z axis.

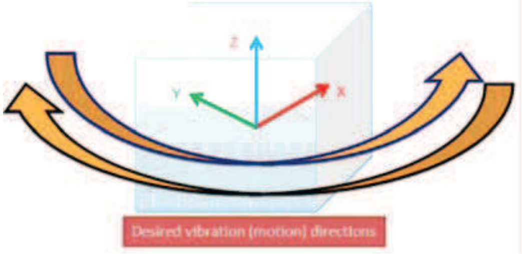
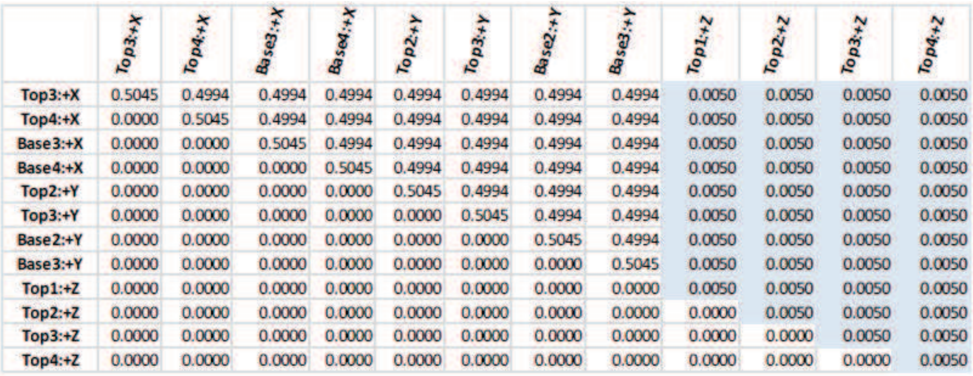
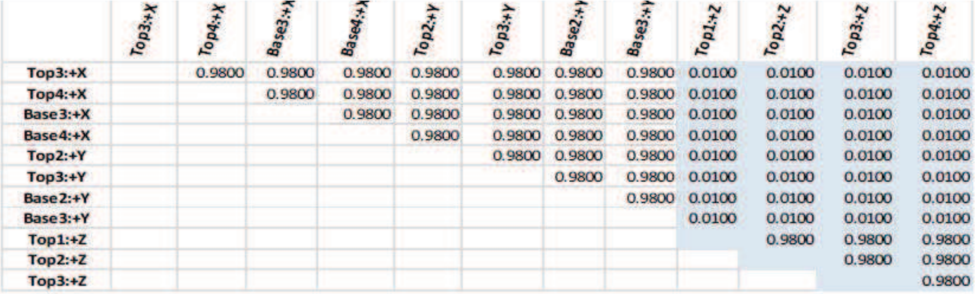


Figure 3. Z Rotation scheme



	Top3:+X	Top4:+X	Base3:+X	Base4:+X	Top2:+Y	Top3:+Y	Base2:+Y	Base3:+Y	Top1:+Z	Top2:+Z	Top3:+Z	Top4:+Z
Top3:+X	0.5045	0.4994	0.4994	0.4994	0.4994	0.4994	0.4994	0.4994	0.0050	0.0050	0.0050	0.0050
Top4:+X	0.0000	0.5045	0.4994	0.4994	0.4994	0.4994	0.4994	0.4994	0.0050	0.0050	0.0050	0.0050
Base3:+X	0.0000	0.0000	0.5045	0.4994	0.4994	0.4994	0.4994	0.4994	0.0050	0.0050	0.0050	0.0050
Base4:+X	0.0000	0.0000	0.0000	0.5045	0.4994	0.4994	0.4994	0.4994	0.0050	0.0050	0.0050	0.0050
Top2:+Y	0.0000	0.0000	0.0000	0.0000	0.5045	0.4994	0.4994	0.4994	0.0050	0.0050	0.0050	0.0050
Top3:+Y	0.0000	0.0000	0.0000	0.0000	0.0000	0.5045	0.4994	0.4994	0.0050	0.0050	0.0050	0.0050
Base2:+Y	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5045	0.4994	0.0050	0.0050	0.0050	0.0050
Base3:+Y	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5045	0.0050	0.0050	0.0050	0.0050
Top1:+Z	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0050	0.0050	0.0050	0.0050
Top2:+Z	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0050	0.0050	0.0050
Top3:+Z	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0050	0.0050
Top4:+Z	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0050

Figure 4. CPSD of "Z rotation"



	Top3:+X	Top4:+X	Base3:+X	Base4:+X	Top2:+Y	Top3:+Y	Base2:+Y	Base3:+Y	Top1:+Z	Top2:+Z	Top3:+Z	Top4:+Z
Top3:+X		0.9800	0.9800	0.9800	0.9800	0.9800	0.9800	0.9800	0.0100	0.0100	0.0100	0.0100
Top4:+X			0.9800	0.9800	0.9800	0.9800	0.9800	0.9800	0.0100	0.0100	0.0100	0.0100
Base3:+X				0.9800	0.9800	0.9800	0.9800	0.9800	0.0100	0.0100	0.0100	0.0100
Base4:+X					0.9800	0.9800	0.9800	0.9800	0.0100	0.0100	0.0100	0.0100
Top2:+Y						0.9800	0.9800	0.9800	0.0100	0.0100	0.0100	0.0100
Top3:+Y							0.9800	0.9800	0.0100	0.0100	0.0100	0.0100
Base2:+Y								0.9800	0.0100	0.0100	0.0100	0.0100
Base3:+Y									0.0100	0.0100	0.0100	0.0100
Top1:+Z										0.9800	0.9800	0.9800
Top2:+Z											0.9800	0.9800
Top3:+Z												0.9800

Figure 5. Coherence of "Z rotation"

Reference models presented in tables require the system to perform rotation around Z axis. Therefore value of all power spectral densities and cross power spectral densities describing channels representing accelerations along axes X and Y are set to corresponding values. Z axis cross power spectral densities and power spectral densities are set to low value, not exactly zero because such performance would be hard to obtain in control system. Regarding coherence between channels, correlation between channels X and Y are set to be almost equal 1, this means that each of the signals should be in phase. When those channels are in phase and Z channel is out of phase regarding X and Y while between Z channel coherence is almost 1 phenomenon of rotation around Z axis occurs without rotation around other axes.

2nd example was implementation of model that would perform only linear motion along Z axis – "Ztranslation".

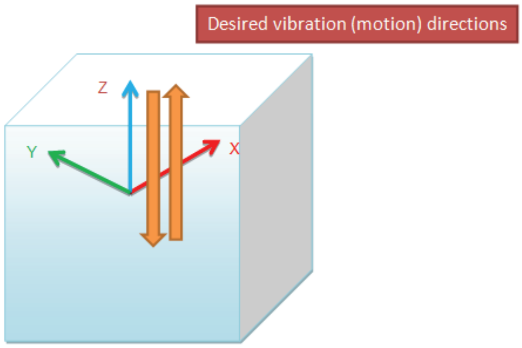


Figure 6. Z Translation scenario

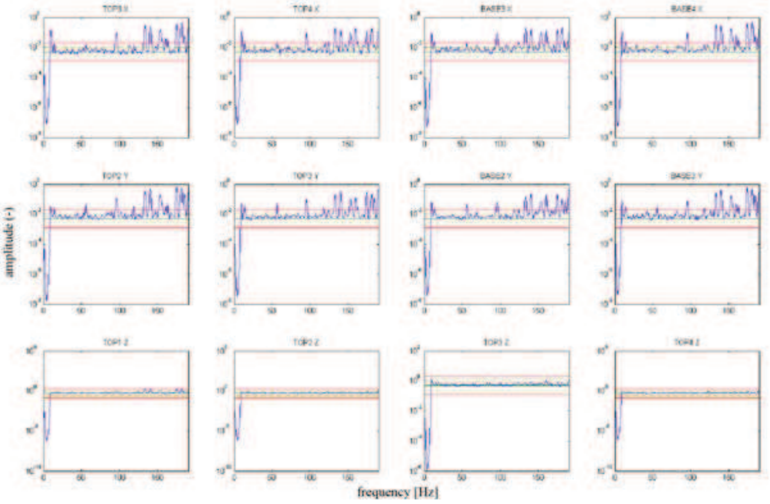
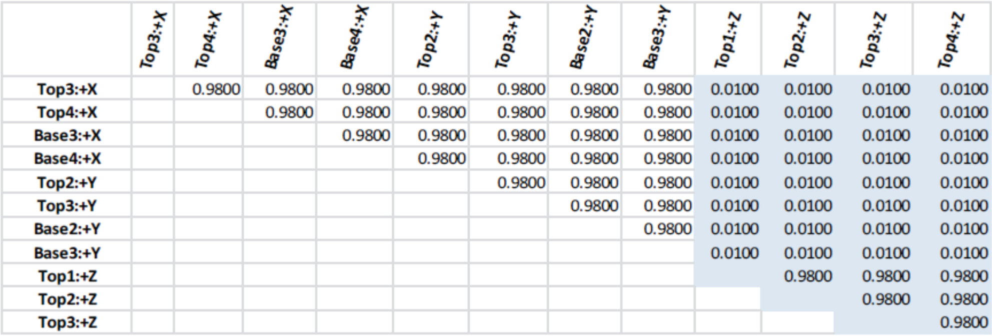
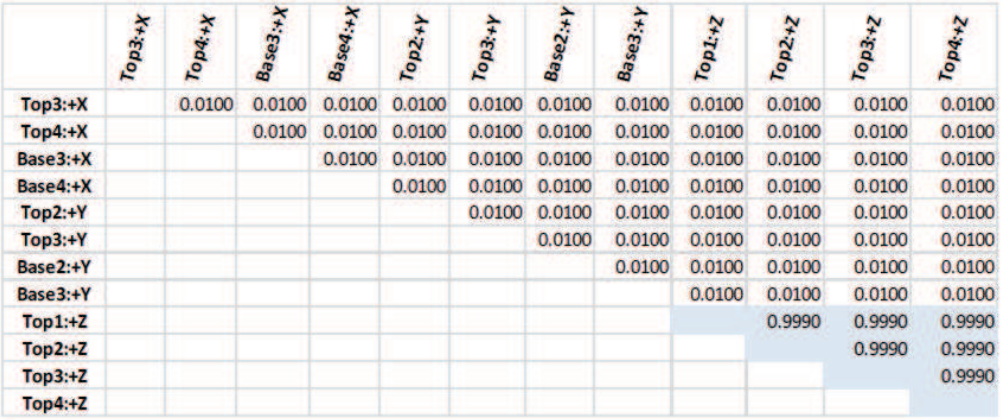


Figure 7. Simulated Response



	Top3:+X	Top4:+X	Base3:+X	Base4:+X	Top2:+Y	Top3:+Y	Base2:+Y	Base3:+Y	Top1:+Z	Top2:+Z	Top3:+Z	Top4:+Z
Top3:+X		0.9800	0.9800	0.9800	0.9800	0.9800	0.9800	0.9800	0.0100	0.0100	0.0100	0.0100
Top4:+X			0.9800	0.9800	0.9800	0.9800	0.9800	0.9800	0.0100	0.0100	0.0100	0.0100
Base3:+X				0.9800	0.9800	0.9800	0.9800	0.9800	0.0100	0.0100	0.0100	0.0100
Base4:+X					0.9800	0.9800	0.9800	0.9800	0.0100	0.0100	0.0100	0.0100
Top2:+Y						0.9800	0.9800	0.9800	0.0100	0.0100	0.0100	0.0100
Top3:+Y							0.9800	0.9800	0.0100	0.0100	0.0100	0.0100
Base2:+Y								0.9800	0.0100	0.0100	0.0100	0.0100
Base3:+Y									0.0100	0.0100	0.0100	0.0100
Top1:+Z										0.9800	0.9800	0.9800
Top2:+Z											0.9800	0.9800
Top3:+Z												0.9800

Figure 8. CPSD of "Z translation"



	Top3:+X	Top4:+X	Base3:+X	Base4:+X	Top2:+Y	Top3:+Y	Base2:+Y	Base3:+Y	Top1:+Z	Top2:+Z	Top3:+Z	Top4:+Z
Top3:+X		0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Top4:+X			0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Base3:+X				0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Base4:+X					0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Top2:+Y						0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Top3:+Y							0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Base2:+Y								0.0100	0.0100	0.0100	0.0100	0.0100
Base3:+Y									0.0100	0.0100	0.0100	0.0100
Top1:+Z										0.9990	0.9990	0.9990
Top2:+Z											0.9990	0.9990
Top3:+Z												0.9990
Top4:+Z												

Figure 9. Coherence of "Z translation"

In case described above the desired motion of system was only translation along the Z axis, this setup requires only coherence between Z channels. During testing vertical motion should not be influenced by motion from other directions (X and Y) therefore cross power spectral density is set to 1 between Z channels.

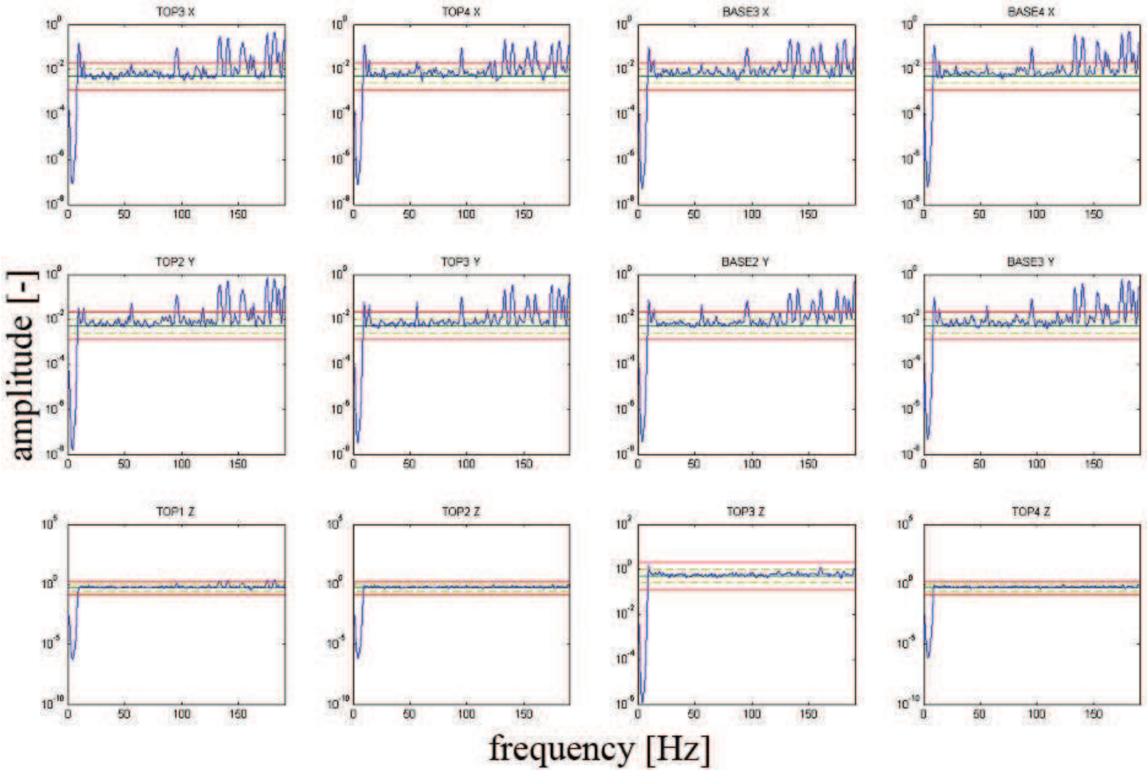


Figure 10. Simulated Response Z Translation

4. SIMULATION AND EXPERIMENT RESULTS COMPARISON

As in case of first discussed control method (3.1.) same procedures and same virtual model will be applied. The system will be tested as in previous example in frequency range from 0 to 200Hz, this time the simulation results will be compared with measurements performed on Team CUBE device in a setup described in first algorithm. The test which was performed on the real structure used algorithm from (3.2.)

4.1. Z-Rotation case

During "Z-Rotation" case the system needs to be excited in a way that motion of the structure is performed only as a rotation around Z-axis, same reference profiles where used as in case of previous implementations.

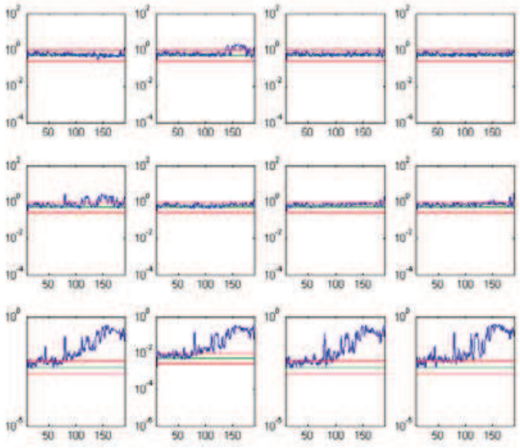


Figure 11. new control results - z-rotation

Control results obtained after performing 36 iterations are satisfactory, even though in case of Z signals we can see big offset from desired values, exciding +/-3db range, but in case of this test it still value that could be neglected because target value is zero and results are of order so could be called acceptable, comparing this results to measurement results it could be said that control in case of real measurements works better.

4.2. Z-Translation case

During "Z-Translation" case the system needs to be excited in a way that motion of the structure is performed only as a translation along Z-axis, same reference profiles where used as in case of previous implementations.

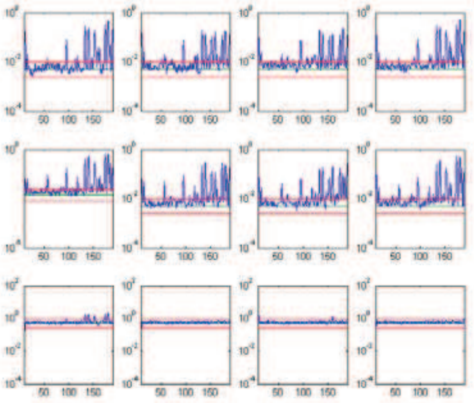


Figure 12. new control results - z-translation

In the same manner as in case of previous simulation, signal which is set as reference do be equal zero, exceeds the limits. Regardless of this fact the result is satisfying as the output signal does not have big value that could influence the test overall.,

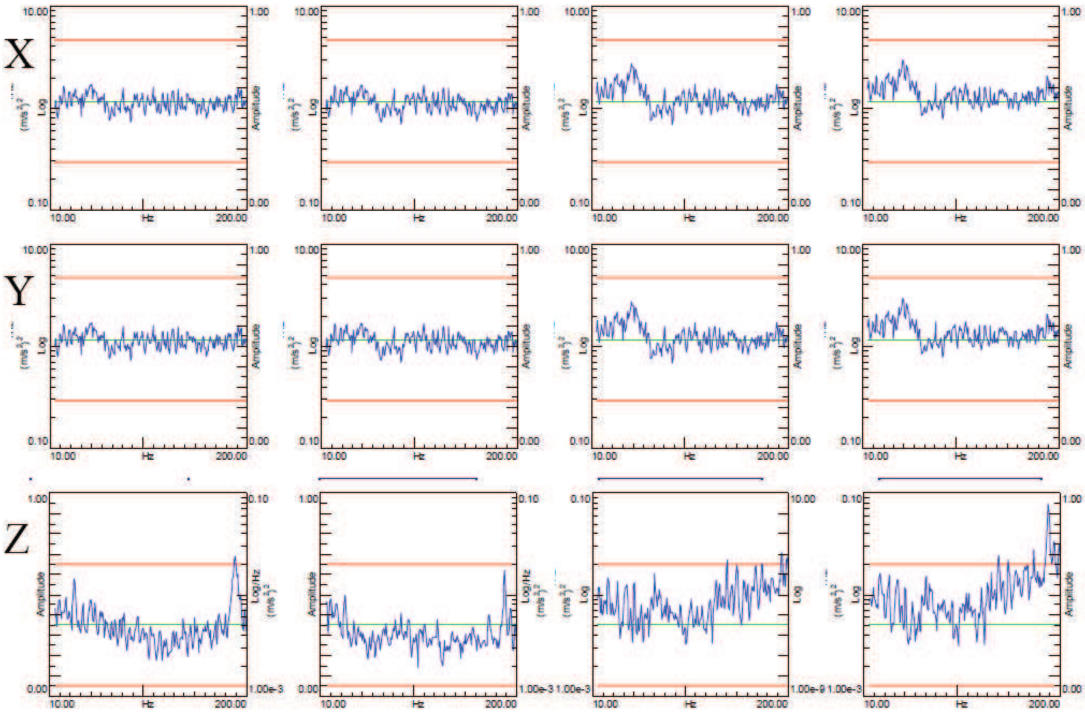


Figure 13. Measurement Results, Z Rotation

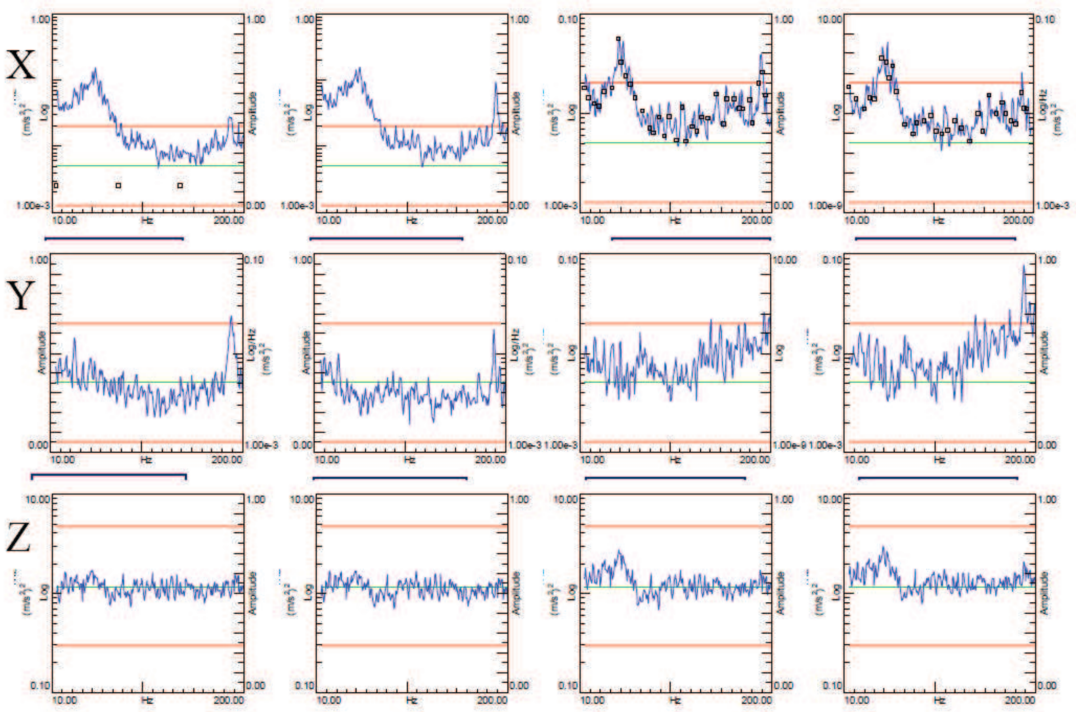


Figure 14. Measurement Results, Z Translation

similar behavior could be observed in measurements performed on real structure.

Comparing the results we can state, that the values of coherence from simulation and measurements are correct, in every case values of coherence are directed in the way that reference model is set up, therefore proper operation of excitation system is obtained.

5. CONCLUSIONS

Summing up the whole research with base of results, a lot of questions rise up. Even though merging presented algorithms resulted in obtaining method which is more efficient in calculations, uses much less control loop iterations for performing calculations the system is not perfect, in many cases it was not able to control spectra at lower frequencies and had problems with controlling systems with higher number of sensors. Yet it could be used as a base for developing next methods of control, such as MIMO sine sweep, and MIMO time waveform replication, which is the most complex from control point of view from all vibrational MIMO testing schemes.

The algorithm operation was only verified with simulation methods in Matlab, therefore its comparison with real measurements is presented to be a visualization of its capabilities. Real verification of its operation would be confirmed by performing environmental test and investigating the results, which may by coherent with simulation as the new method is solely based on previously existing and functional control methodologies.

If such tests would prove proper operation of this new control methodology, next step in development could be undertaken.

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