# A VIBRATION EFFECT AS FATIGUE SOURCE IN A PORT CRANE SIMULATOR FOR TRAINING AND RESEARCH: SPECTRA VALIDATION PROCESS

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**ABSTRACT**
This paper is concerned with the loading and validation of vibration spectra, monitored in a ship-to-shore crane in operation at the Port of Cagliari, the distributed real-time interoperable simulator includes a motion platform. In fact Simulators are typically used in active safety applications and in this specific case, our simulator was designed for the purposes of both training and basic and applied research, as it is possible to monitor physiological parameters recorded using appropriate electromedical instruments. The onset of fatigue in quayside crane operators can be attributed not only to awkward posture, but also to the high vibration levels generated by the nature of crane operations, transmitted to the operator through the cab seat.

Key Words: vibrations, motion platform, fatigue, simulator, VV&A process

## 1. INTRODUCTION
The aim of this paper is to describe the methodologies used to evaluate and verify and validate, within the virtual reality environment, the intense vibratory action which the operator experience during training sessions.

Figure 1: Ship Size and Crane Interference

By identifying the key task phases and recording the synchronous vibration spectra, it was possible, with this highly versatile and flexible simulator, to repeat the procedure for all types of cranes operating worldwide, thus improving fidelity by tailoring to suit specific needs. The research database, compiled using information gathered during training sessions and also containing data on the effects of vibrations, a major source of latent stress in quayside crane operators, will also be more reliable. The authors developed a real-time simulator named ST_PT_1 (Bruzzone et al.2008); this is a HLA (high level architecture) distributed simulation implemented in a standard container shelter for guarantee mobility; the ST_PT_1 incorporate multiple vehicle simulation interacting in a federation, however it focuses on a quay crane full scope simulator including CAVE, 6 D.O.F. motion platform, sound 3D, panel controls and it represent and important step forward for research in port activities; in fact this system could provide significant contribution in researches devoted to improve the whole supply chain that is strongly affected by logistics node performances and port facilities capabilities; in this context safety and productivity issues are strongly related, while the necessity to handle in short time very large ship, characterized by a continuous trend in growth, represent a major challenge (Ircha 2001). This crisis situation is reducing the impact of the problem related to being able to unload/load large container ship, however it is expected that as soon as the traffic will be back to regular levels, this characteristics will correspond to a strategic competitive advantage (Merkuryev et al. 2009); so in fact contingency crisis is providing the opportunity to develop new solutions as well as to proceed in their test and evaluation for being ready for next economic phase.

## 2. SIMULATION AS PORT ENABLER
The figure 1 puts in evidence the critical aspect correlating ship size and port capabilities; obviously this picture is providing just a view of largest current ships versus gantry crane size, without paying attention to interference issues; however a basic computation considering:

| | |
|---|---|
| $S_c$ | current largest container ships capacity (about 11'000 TEU) |
| $C_p$ | mean gantry crane productivity (about 25 containers/hour) |
| $P_n$ | nautical port operations (arrival and departure, about 0.75 hours each) |
| D | cruise distance (i.e. Hong Kong-Los Angeles 6363 nautical miles) |
| $S_s$ | cruise speed (for latest generation ships about 25 knots) |

$P_{ltp}$ port time lapse (about 10% of full cycle time for effective use of the ship)
$k_{tf}$ factor corresponding to the ratio between 20 feet and 40 feet container on board (for instance 1/3)
$k_{xm}$ factor corresponding to the influence of extra movements (about 10% considering hatch operations)
$k_{oe}$ factor corresponding to the percentage of containers unloaded for import (about 90% considering this large ships on oceanic cruises)
$k_{oi}$ factor corresponding to the percentage of containers loaded for export (about 90% considering this large ships on oceanic cruises)
$P_{ltp}$ port time lapse (about 10% of full cycle time for effective use of the ship)

$$C_n = \frac{(k_{tf}+1)\cdot(k_{xm}+1)\cdot(k_{oe}+k_{oi})\cdot S_c \cdot S_s \cdot (1-P_{ltp})}{C_p \cdot (k_{tf}+2)\cdot\left[D\cdot P_{ltp} - 2P_n \cdot S_s \cdot (1-P_{ltp})\right]} \quad (1)$$

In the hypotheses (pretty optimistic) presented the number of crane requested to complete in time the operation ($C_n$) resulted in about 20 concurrent gantry crane; this result is critical considering the mutual interference, the necessity to keep pretty good productivity; considering the ship size growth it is required to improve productivity of the cranes; current evolutions is moving forward improving the gantry cranes, i.e. new spreaders (i.e. multiple lift), very high speed and accelerations. However all these aspects introduce the necessity to simulate the whole process to create virtual prototypes to test the real effectiveness of proposed changes; in addition it becomes very critical to train people operating systems that run much faster with higher weights and in very high density operation. So it is evident that simulation represent an enabler for improving port capabilities (Bruzzone et al.2006)

In fact Simulation models are used efficiently by engineers as a decision support tool for dealing with strategic, tactical or operational decisions in logistic systems (production logistics such as warehousing and hospital logistics and transportation, Merkuryev Y., Merkuryeva, G., Piera, M.À., 2009).

Simulators are being increasingly used to research human factors optimization in the transportation sector as these tools enable to reproduce and evaluate, singly and in combination, all those factors contributing to fatigue (Fancello et al. 2008b). Task simulators are also models, but offer the advantage of having been specifically designed to simulate the distinctive characteristics of real world tasks in a virtual reality environment.

The quay crane simulator installed at Cagliari University (Bruzzone A. et al., 2008), which ultimately aims to enhance safety and productivity in container terminals, is an innovative system designed for the purpose of solving human factor related problems (ergonomics, anthropometrics, etc.) relative to tasks performed by quayside crane operators (D'Errico 2009) (Figures 2/3).

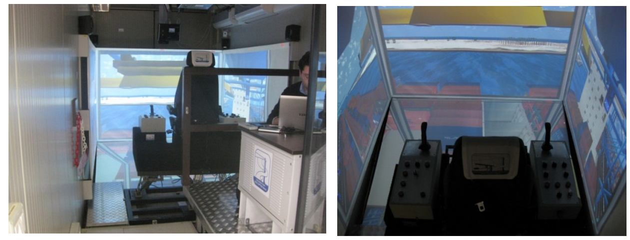

Figure. 2/3: Details of dynamic driver cockpit (6 degrees-of-freedom motion platform) and graphic interface of ST_PT_1 quay crane simulator.

The mobile simulator is housed in a 40 ft High Cube container, purposely chosen for its internal height of 2.70 m, higher than a standard ISO container, thus allowing more space for the main platform as will be described in detail later. This minimizes the time required to prepare training and research sessions, providing on site training services for container terminal operators.

The programme envisages three different types of activities:

- Research: studies of operator performance under various operating conditions using objective medical parameters (*EEG*, *ECG*, *EMG* plots, *goniometer, inclinometer, accelerometers, eye tracker*, etc.) and of the procedure already adopted in a real world environment for handling and analysing fatigue test data (performance curves, neural networks);
- Technological advance: applied research and validation of new design solutions for the crane control systems and commands, for enhancing operator performance and thus aimed at optimising the man-machine interface;
- Training and refresher training of crane operators in container terminals; this activity is important for two reasons: economic, in that research can be funded by selling training packages to container terminal operators, and functional, as the data gathered during training sessions will be used to create and build up the research database.

This entirely original virtual reality instrument, that is able to satisfy the real needs of the container transportation sector, is equipped with an extremely versatile and flexible hardware and software system that is unlike any other existing quayside crane training simulator (Bruzzone et al. 2008). This feature means that operator training can be adapted to all cockpit and quay crane types existing worldwide.[1]. In actual fact, the ultimate design of the simulator was the result of a major effort including detailed literature reviews, research, in depth studies and propedeutic analysis of crane operator tasks conducted in a real world environment by the CIREM-Human Factors research team at Cagliari University, as contribution to the realization of this innovative machine. (D'Errico G., 2009).

### 2.1 Study of human factors in quayside crane operations in a real world environment

CIREM (Interuniversity Centre for Economics Research and Mobility) at Cagliari University has provided some important contributions consisting of surveys, studies and subjective analyses conducted at CICT (Cagliari International Container Terminal) at Cagliari Industrial Port (Fancello et al. 2008a). The research conducted used an integrated database containing:

- the first arousal-performance curves to be plotted in this particular scientific context of quayside crane operators, were built using a familiar model (a study on human behaviour simulation using a dynamic stress model adopting the same model of experimental performance curves has been conducted by Seck et al., 2005), theYerkes-Dodson function (Fancello G. et al., 2008a/b), that relates work load with performance level;
- the results of a questionnaire completed by crane operators at Cagliari Industrial Port concerning a number of ergonomic aspects (physical complaints indicated) and task related fatigue;
- a series of anthropometric measurements taken using films of CICT quayside crane operators during task execution (Meloni M. et al., 2009);
- two vibration measurements recorded by means of accelerometers, placed in previously identified strategic points inside the crane cab during operation, the first for the duration of the work shift, the second for each key phase of the job task identified with the first..

Using these data, which are dealt with in this paper, it was possible to obtain in output the vibration spectra for the linear and angular accelerations over time. These were then loaded into the software used to handle the simulator's motion platform, making it possible to faithfully reproduce, except for a few corrections, the vibrations experienced by the operator during the simulation scenarios. In this way it will be possible, using the electromedical instruments with which the simulator is equipped, to evaluate fatigue, also taking into account operator exposure to the vibration effect generated by the motion platform (Burdorf et al. 1993).

## 3. BACKGROUND AND PRELIMINARIES

The containers are loaded/unloaded using ship to shore cranes by means of a "spreader", that is mechanically connected to the hoist motors via a beam suspended from cables and electrically connected to the crane. The container is hooked/unhooked by means of four corner flippers on the spreader (Ircha 2001).

The containers are transferred from ship to shore through a combination of two movements: the spreader-container system is hoisted to the maximum clearance height, and the crane then travels with its load along the bridge rails to the container stacking bay. This operation is usually repeated at least 20 times per hour, the cab travelling back and forth from the ship to the yard (Bruzzone et al. 2007).

Thus throughout the six hour shift the crane operator is exposed both to high vibration, due to cab movements, and to high noise levels generated by the very nature of the operation,. Added to this, is the discomfort caused by the bent forward posture and awkward head/neck positions that the operator is forced to assume to closely follow the movement of the container some 40 m below. These conditions give rise to psycho-physical stress that medically speaking can cause serious health problems over time, while from an operational standpoint they bring about a deterioration in performance that translates into reduced productivity.

### 3.1 State of the art on the combined effect of ergonomics-vibrations as a stress factor in dock workers

Ergonomics and in particular workstations re-design is a widely studied "human factors" branch that examines operator performance in relation to awkward and poor posture (Meloni et al. 2009). In a study on the effective ergonomic design of workstations, using a simulation model that recreates in a 3-D virtual environment industrial plant workstations, the specific design methodology used by researchers (Cimino et al. 2009). compares the present day workstations with alternative configurations, carrying out specific analyses supported by a well-planned experimental design (based on multiple design factors and multiple performance measures). There is a plethora of international scientific literature on the effects and permanent physical damage that awkward work postures can cause to dock workers, damage compounded by the high vibration levels generated by the machines they operate. These complaints are commonly referred to as *Work-related MusculoSkeletal Disorders"* (WMSDs). By way of example, a representative study on occupational risk factors for low back complaints in sedentary workers (Burdorf A, 1993), examined the relationship between low back disorders and sedentary work in yard crane operators (94 subjects), straddle carrier drivers (95 subjects) and a group of office workers (86 subjects), aged between 25 and 60. The information on the extent of low back complaints and of the subjective working conditions were extrapolated from a cognitive survey. The postural load on the back was evaluated by observing awkward trunk postures during normal work activities. Whole-body vibration exposure of crane and straddle carrier drivers was also measured. Fifty percent of crane operators suffered from low back complaints within the first 12 months of starting work, against 44% of straddle carrier drivers and 34% of office workers. These findings indicate that sedentary work involving poor and constrained trunk posture represents a serious risk factor for low back disorders. Concerning the correlation between poor posture and vibration exposure, a specific report (Lane R., 1999) compiled in British Columbia (Canada) provided evidence of a connection between body vibration exposure and back disorders, in a variety of motor vehicle driving tasks (Bianconi et al. 2006). The report consists of a collection of scientific literature and of a number of electronic databases (Medline, EMBASE, NIOSHTIC, Ergoweb and Arbline), collating pertinent data for each topic. The scientific investigations chosen adopted a standard epidemiological approach to show the association between back disorders and vibration exposure. The risk factor was found to be high for a wide variety of tasks performed by lorry drivers, agricultural workers, tractor drivers, bus drivers, helicopter pilots, bulldozer drivers, fork-lift truck and yard crane operators. Risk assessments indicated strong associations between back disorders and vibration exposure, the risk increasing with increasing of work shift and vibration exposure duration whereas no increase was observed for increasing vibration intensity. Twenty-five studies covering a variety of job tasks showed that the machines used exposed operators to vibration levels well above the threshold limit established by the British Columbia's new health and occupational safety directives. The findings show a strong correlation between back disorders and whole-body vibration, the most common complaints being low back pain, sciatica, generalised back pain, disc herniation and intervertebral disc degeneration.. The risk is higher after the first five years of exposure.

### 3.2 Motion platform in quayside crane simulators

The cockpit, or simply the work station in the less sophisticated simulators, is generally placed on a motion base, with a varying number of degrees of freedom (2, 3, 4 or 6 with different loads). Thus the simulator does not only generate visual and auditory stimuli but above all allows the operator to perceive the sensation of movement

The platform consists of a combination of electric/hyraulic or pneumatic actuators installed beneath the cockpit that impart movement in response to operator input and to the task phases executed. The motion system duplicates the vibrations and shocks generated in normal operating conditions, synchronised in the simulation software with the audio and video systems. Various types of motion base exist (Figures 4b/c), the most widely used being the *"Stewart Platform"* (Figure 4a), which like all simulators was originally devised for flight simulators in the aerospace and aviation sector. The six possible movements (maximum degrees of freedom) that the motion base imparts are divided into two categories of motion: linear translational (*heave*, translation along the $z$ axis; *surge*, translation along the $x$ axis; *sway*, translation along the $y$ axis – Figures 4d-f) or rotational (*pitch*, rotation around the $y$ axis; *roll*, rotation around the $x$ axis;; *yaw*, rotation around the $z$ axis; – Figures 4g-i).

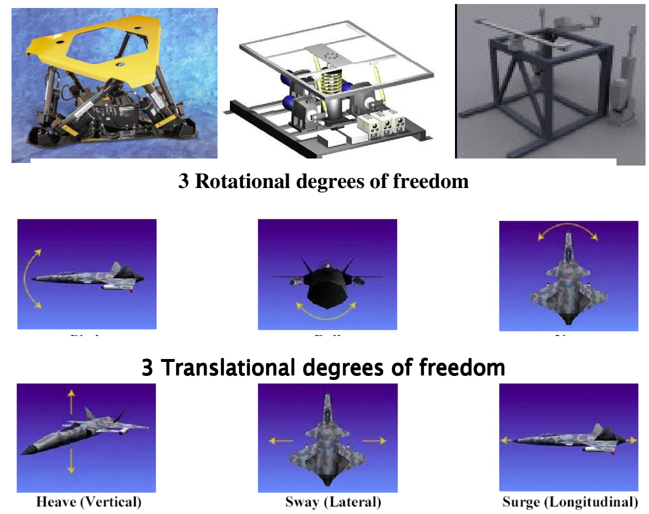


Figure 4a-i – Three different types of motion base (the first is a Stewart Platform) and the 6 degrees of freedom it achieves, depicted by the motion of a military aircraft in flight.

## 4. METHODOLOGY

Design the preparatory studies for the simulator design it was necessary to identify what type of real input data to load into the simulator software that also handles the motion platform so as to ensure correct response to the user commands, to the movements and to the task phases, as well as perfect synchronization with the audio and video systems.

The choice fell on vibration spectra. As mentioned in the introduction, a vibration measurement campaign was conducted preceded by a preliminary study to identify the strategic positions of the accelerometers inside the cockpit (based on previous experience with the CICT crane cabs). This campaign was carried out jointly with the Department of Mechanical Engineering at Cagliari University.) inside the cab of a CICT quayside crane in operation.

The accelerometers were positioned (Figure 5) such that the different linear and rotational acceleration components could be calculated using simple arithmetic; in particular:

- linear accelerations along $X$ : Mean of signals $x1$ and $x2$;
- linear accelerations along $Y$ : Signal $y1$;
- linear accelerations along $Z$ : Mean of $z1$ and $z2$;
- angular accelerations around $X$ : $(z2 - z1)/a$;
- angular accelerations around $Y$: $(z3-z2)/b$;
- angular accelerations around $Z$ : $(x1 - x2)/c$

First of all (at Cagliari International Container Terminal on 21 September 2007) the work cycle of the quayside crane was examined, for a continuous 6-hour shift divided into the following key phases:

- Phase 0: Position spreader, secure container and hoist from quayside;
- Phase 1: Spreader travels with container along quayside to ship;
- Phase 2: Position container on ship and unlatch;

- Phase 3:Spreader returns to quayside starting position for next cycle.

The RMS values for each linear and angular acceleration component were calculated together with the maximum absolute values. Both values refer to consecutive samples of 1000 data, obtained at a scan rate of 2000 data/second, for a typical complete work cycle. In this way, it was possible to identify the critical acceleration values in the different phases.

Figure 6 shows the different phases identified, denoted by different colours. The same colours were used in Figs. 6a-c, which show, for the sake of simplicity, linear acceleration with respect to the three axes.

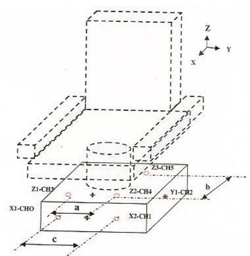
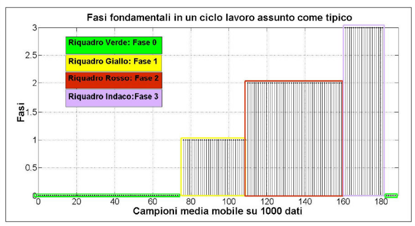


Figure. 5/6 – Position of motion sensors and work phases identified for a complete 6-hour shift

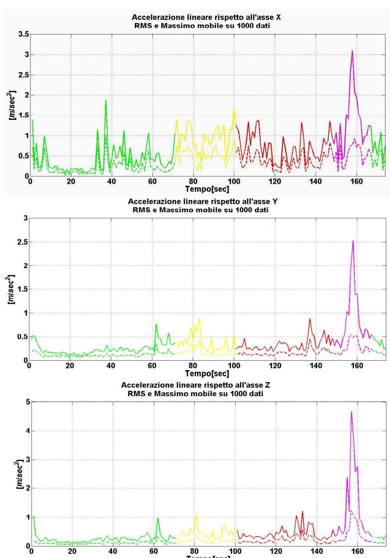


Figure 7a-c – Moving average over 1000 data of RMS values and maximum absolute values of measured linear accelerations

The vibration spectra proved to be essential for properly duplicating the psycho-physical stresses experienced by the operator through the motion base in question, during the training sessions.

However, the following difficulties and shortcomings were encountered during the first vibration measurement campaign:

- difficulties in loading the vibration spectra into the simulator software and especially in associating the recorded spectrum with the corresponding phase;
- difficulties in identifying the phases comprising the quayside crane operator's tasks to be duplicated singly with the simulator and in allowing the instructor to alternate simulation scenarios and to get the trainee to repeat the test.

In fact the original data sample was mixing different operation and it was very difficult to reattribute their characteristics to the simulation actions in addition it was necessary to consider the influence of boundary conditions; currently the approach is based on defining DRT (Data Reference Tables) related to each single operations and the relative boundary conditions, including current spreader weight (including container if present), crane speeds, wind speed, wind direction, etc.

The DRT include the reference to the pre-processed vibrations to be reproduced in the simulator corresponding to an original data sample; obviously pre-processing is required to adapt data sample to simulator device capabilities in order to guarantee fidelity.

ST_PT_1 analyze DRT during real-time operation, when a specific action is performed among that ones generating vibrations (i.e. movement of the crane); by mining the DRT the simulator finds the most appropriate configuration in the DataBase in relation to the current action and based on a weighted distance from the simulated boundary conditions and DRT.

For each action it is defined a default sample, in order to guarantee a basic vibration to be transferred to the simulator

So the proposed approach guarantees to being able to reproduce a specific crane just with few available data, and keep it open the possibility to extend this library over the time with new samples.

Based on these consideration it was necessary to conduct additional samples in order to correlate the vibrations with the boundary conditions.

These measurements did however bring to light one aspect that contributed to interfering with the crane operator's task. Vibration exposure limits are established by Decree Law No. 187 of 19 August 2005, implementing EC Directive 2002/44 on the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents. The vibration time histories generated during the work cycles, namely measures of acceleration along the three axes x, y and z, were recorded using motion sensors placed in appropriate points of the cab seat. Out of the 174 measurements along the x axis (corresponding to the back and forth motion of the cab for each operating cycle, roughly one every 1'30"-2') the RMS acceleration, which is in itself a mean value, exceeded the permissible daily action value of 0.5 $m/s^2$ for whole body vibrations 44 times, reaching as much as 1.00 $m/s^2$ and for groups even 5-7 continuous linear accelerations exceeding the limit.

RMS acceleration along the z axis only exceeded the daily action value five times, but on the other hand the peaks attained extremely high absolute values (one recording showed a RMS acceleration of 1.24 $m/s^2$

corresponding to a Max of 4.68 m/s$^2$). These operating conditions coincide with the cab position at the boom tip where the jerks caused by container locking/unlocking reverberate strongly at the free end of the gantry crane boom.

Accelerations along the y axis did not generate any significant whole body vibrations because of the nature of the operations in relation to the crane structure, which do not produce large shocks along the transverse direction.

In spite of the useful information gathered, it was decided to optimize operation of the vibration spectra loading process into the simulation software that also handles the motion base of the ST_PT_1 simulator, so as to duplicate the vibrational stresses associated with each phase of the task (Bruzzone et al. 2004).

### 4.1 Building a motion DataBase: Second non-continuous survey in a real world environment

The second series of measurements conducted at the CICT on 18 February 2009 was designed for the purpose of associating each recording taken with the accelerometers, once again placed on the cab seat (Figures 18-20), to the key task phases. This was done with the assistance of a crane operator who performed each task requested, with the technicians recording simultaneously.

The following activites were conducted by the team of collaborators from CIREM at Cagliari and DIPTEM at Genova, the latter responsible for constructing the quayside crane simulator:

- Identification of key operating phases to be monitored;
- Synchronised recording using accelerometers of each operating phase accomplished by the crane
- Creation of "talking" codes to load into the simulator software *(e.g. Cabt_S_Scenario 4.02_9_315_210_1000)* for perfectly reproducing the psycho-physical stresses on the operator's body (cyclic VV&V procedure).

For defining the "talking" codes, the name of the sample describing the scenario was indicated. For example

***ID_K_Scenario 1_06_090_150_10***

*where:*

- ID denotes the type of test;
- K denotes the load: S no-load, 4 4 tonnes, 30 30 tonnes, etc.;
- ex1 denotes the sample code (if measurements have been repeated for the same scenario then these will be numbered consecutively for example Scenario 1.01; 1.02 etc.);
- 06 indicates wind speed in knots;
- 090 indicates wind direction (degrees);
- 150 indicates travel speed expressed in m/min;
- 10 indicates instrument sampling rate in Hertz.

The talking codes were grouped into quayside crane travel, spreader movement and a number of additional manoeuvres that were identified on site during measurements.

Furthermore, the CICT crane operator was asked to repeat all the above movements for three different load configurations: Bromma spreader in standby (no load S:); spreader with container attached, medium load (load 4: 4 tonnes); spreader with container attached, full load (load 30: 30 tonnes). In this way it was possible to compile a database containing a wealth of information about the operating phases in the different configurations, in order to adequately duplicate the real world stresses experienced by the operator .

The measurements were taken in the six measuring points schematically indicated in Figures 8-10. The use of measurements taken along the three axes underneath the operator's seat, i.e. on the supporting structure, and on the seat frame itself, also allows to evaluate the vibration absorption effect exerted by the buffer placed between the support and the seat itself. During simulations it will be possible to evaluate other types of vibration dampening systems..

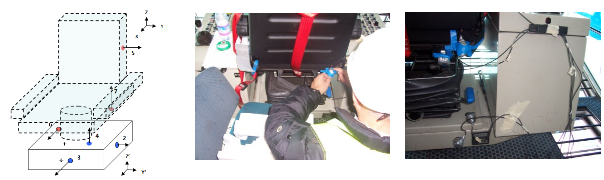

Figure 8-10 – Positioning the accelerometers on the CCIT crane operator seat for point measurements

Two types of measurements were obtained. Accelerometer recordings versus time sampled at a rate of 1 Hz, during the key phases of the work cycle and spectra recordings, consisting of consecutive series of 500 data representing the spectral components at a sampling step of 1 Hz. As the typical duration of operating phases is in the order of 10-15 seconds, each recording contains several thousand data.

Figures 14-16 show portions of some of the spectra recorded for the key operating phases:

- Talking code *Engc_4_Scenario 20.01_17_315_XX_1000* recording of phase Engage Container (Engc) load 4 tonnes (4) with 40 ft Bromma spreader, Scenario N°20, first recording (01), wind speed 17 knots, wind direction 315°, XX speed of the unknown operation for this phase, sampling rate 1000 (Figure 11);
- Talking code *Cabt_4_Scenario 4.02_9_315_210_1000* recording of phase Cab travel from shore to ship side max speed (around 15-20 m travel) (Cabt) with 4 tonne (4) container attached to 40 ft Bromma spreader, Scenario N°4, second recording (02), wind speed 9 knots, wind direction 315°, carriage travel speed 210 m/min

for QC type in operation at Cagliari container terminal sampling rate 1000 (Figure 12);

- Talking code *Jerkh_30_Scenario 23.01_6_315_85_1000* recording of phase Repeated movement (jerks) with cab at half boom operator manoeuvring cable take up drum joystick (Jerkh) with 30 tonne (30) container attached to 40 ft Bromma spreader, Scenario N°23, first recording (01), wind speed 6 knots, wind direction 315, cable winding/unwinding speed 85 m/min for QC type in operation at Cagliari container terminal , sampling rate 1000 (Figure 13);

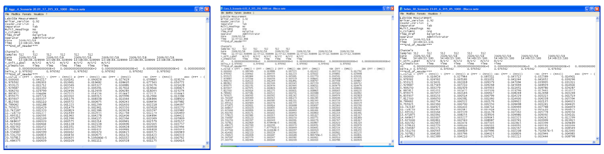

Figure. 11-13 – Portions of three recorded spectra extrapolated from the database created by the Department of Mechanical Engineering at Cagliari University.

Concerning the spectra, the sampling interval is a little less than 1 Hz because the Fourier transform is performed on 1024 and not on 1000 data in order to maximise algorithm efficiency.

It was also possible, as for the previous measurements, to easily evaluate the severity of vibrations experienced by the operator on the basis of existing legislation concerning occupational exposure to vibrations: extremely high acceleration levels were observed during emergency stops.

The most interesting aspect of the second series of measurements concerned the possibility of creating a universal database, that can be readapted to subsequent vibration measurements on other types of quayside cranes operating worldwide. The choice of vibration spectra as input data, and the current handling mode consisting of talking codes for associating vibrations to each operating phase, will facilitate loading, after measurements of vibrational stress data for all other types of quayside cranes. This makes the crane simulator at Cagliari University an extremely flexible and versatile tool for training activities but it can also be used to monitor and record fatigue, duplicating the real world psycho-physical conditions to which crane operators are exposed in the container terminals who apply for training courses.

### 4.2 Motion Generation

The original layout of the quayside crane simulator cockpit envisaged a Stewart type motion platform with six degrees of freedom, consisting of six prismatic actuators. This platform was able to move simultaneously in all six degrees of freedom (*Pitch, Roll, Yaw, Surge, Heave, Sway*), but proved too cumbersome to fit inside the shelter housing the simulator.

Thus, an alternative motion base had to be found that fitted comfortably onto the main platform considering the following:

- Maximum travel to be generated to reproduce the movements of the crane used;
- Maximum permissible dimensions;
- Easy access for maintenance.

It was also necessary to reduce the overall height of the main platform (including the workstation Figure 14) to enable the operator to perform tasks standing up (Figure 15).

The motion base chosen (LamceCoppeSIM40, Figure 16) consists of 5 pneumatic actuators (motion system that facilitates calibration operations) positioned as follows: 2 pairs of actuators on the platform sides each connected to the same base, the front ones fixed in a vertical position with the upper part free to rotate 360°, the others at an angle and oriented towards the back part of the platform, the fifth single actuator at the back moves almost 90°. The actuators are interconnected and connected to a console and require a starting power of up to 20 Kw. The platform is equipped with a safety valve for dampening the loud noise that consists either of a number of small sensors or of just one larger sensor that can also be installed outside the shelter.

The user friendly software for the check controls, such as joysticks, lights etc. is designed to check the control panels used by the operator, equipped with 12 Volt sensors, are functioning properly.

Figure. 14-16 –LamceCoppeSIM40 motion platform of the ST_PT_1 simulator

The technical specifications of the motion platform are as follows (Table1):

Table 1 – Technical characteristics of the LamceCoppeSIM40 motion platform

| Degrees of Freedom | MIN | MAX |
|---|---|---|
| Pitch | - 11° | + 11° |
| Roll | - 8° | + 8° |
| Yaw | - 7° | + 7° |
| Heave | - 0,25 mt | + 0,25 mt |
| Surge | - 0,20 mt | + 0,20 mt |
| Sway | - 0,20 mt | + 0,20 mt |
| **Dimensions** | | |
| Height (stand-by mode) | 70 cm | |
| Length | 135 cm | |
| Weight (including workstation) dell'operatore) | ≈150 kg | |
| Maximum useful load | 600 kg | |

The maximum translational and rotational travel is somewhat less than the Stewart motion platform, The height in stand-by mode is roughly the same but with this configuration about half of the platform forms part of the operator workstation.

The psycho-physical stresses generated by the 6 DOF motion platform are: *shocks* (spreader colliding with container to be engaged or with ship's cells, rapid movements of the carriage along the rails and sudden stops at end stops, cab settling, abrupt release of container onto truck in buffer area, etc.) that the platform motion reproduces (pneumatic actuators extend or retract in the six degrees of freedom), vibration effect duplicated by a bus shaker, a kind of subwoofer placed inside the cube-shaped support on which the operator's seat is mounted that generates a sensation of slight shuddering (this system operates at low frequencies, 0-40 Hz) throughout the operator's body (caused for example by oscillations of the cables on which the spreader and container are suspended), that combined with the shocks generate a realistic sensation of the actual stresses experienced .

The principle of the VV&A, concerns the duplication of the innovative and technological data input into the simulator's conceptual (or descriptive) model that should ensure perfect duplicability of the real world environment (Bruzzone and Mosca 1998). This will be described in the next section. This cyclic procedure has also been applied to the vibrations generated by the motion platform, for reproducing in a virtual environment of the above psycho-physical stresses, i.e., those that contribute to the onset of operator fatigue.

The linear and angular accelerations recorded versus time in the second survey, loaded into the software that handles the simulator, with some corrections (raw data filtering and cleaning), allow to reproduce the combined (*shocks-shaker*) vibration effect, Thus the *loop* terminates with the *feedback* (actuator movements) from the platform to the simulator software.

The integration of a real time simulator with a motion system able to reproduce the vibration transmitted to the operator requires an heavy workload and involves different aspect (i.e. engineering of the platform, sampling and processing of data, enginnering of the vibration/motion system, software integration with the simulator). The author focused their research on the sampling and post processing of the signal.

### 4.3 Data collection

In order to have a significant number of samples, releted to the respective operation, the authors start creating DRT that permit to match (the rows) all the operation/movement that the crane operator do, during their job (i.e. lateral movement of the crane on the dock) with the operative and boundary condition (i.e without payload, with a 30 ton container on…). Each cells of the DRT represent a sample that must be collected, as additional information each sample was completed with wind speed and direction.

To collect data a real crane control cabin and seat was "customized" with 2 sets of accelerometers that permit to sample the acceleration/vibration on the 3 axis. The choice to use 6 accelerometers (2 set) is due to the fact that the authors want to know what is smoothing effect of the damper connect to the chair, then the first set detect the vibration transmitted to crane operator and the second one the vibration transmitted to cabin frame.

The data was sampled using a sample frequency of 1 kHz that permit, according to Shannon theorem, to detect 500Hz as max frequency (without aliasing).

### 4.4 Engineering of the motion system

Now the problem is reproduce the vibration sampled the system adopted is a mix of two different actuator:

- Pneumatic actuator
- Electromagnetic actuator

The idea is to reproduce low frequency vibration (less than 10 hertz) with the pneumatic actuator and the high frequency vibration with electromagnetic actuator. The electromagnetic actuators permit to reproduce vibration if connected to an audio amplifier driven directly by the sound card of the workstation used for run the simulator. Using a some of these actuators in a stereo configuration it becomes is possible to reproduce the vibration on the 3 axis. The problem is that the frequency response of the amplifier is linear on a bandwith 20-20000 Hz; this introduce a problem related to the window 10-20 Hz. The solution adopted was to boost the harmonic in that range according with the frequency response curve of the amplifier (i.e. 3dB/decade).

### 4.5 Post processing analisys

The data collected are represented as timeseries (the x axis is time in ms and the y axis is acceleration expressed in m2/s), applying the DFT (Discrete Fourier Transform) to each time series the authors obtained the frequency analysis of each sample. The next step was to correct the gain of each Harmonic in the window 10-20Hz according to the frequency response of the stereo amplifier used, as explained before. In our case for instance the DFT generates 2500 harmonics from 0 to 500 Hz, due to the fact that each sample have a duration of 5 seconds corresponding to 5000 data plots.

The authors analized the spectrum of each signal, for all samples it was decided to consider harmonics higher than 100Hz not significant and so based on the filter setting these component was void for rebuilding the vibration. The next step on the analysis was to identify the most significant harmonics for each sample, to make this the author apply a Pareto analysis focusing only most influent harmonics, contributing till the 90% of the whole vibration. This approach, obviously, generates a new pre-processed data set to be used in the simulator that result different respect original signals and introduces distortions; therefore in the proposed application this different resulted not significant for the main goal of this research that focus on the reproduction of vibration outside audible spectrum. As final pre-processing the reconstructed vibration based on modified harmonic modified spectrum was used to generate reference .wav files (22.1 kHz sampling frequency) using a multitrack recording software in order for being easily reproducible by sound cards and bass shakers

## 5 CONCLUSIONS

The analysis conducted highlighted needs and methodologies devoted to introduce specific vibrations in real-time simulators in order to reproduce specific real equipment. The case study proposed is related to ST_PT_1, a full scope simulator, adopted by C.C.S.Tra. for being used in training and R&D; in these context the requirement for effective reproduction of vibration spectrum becomes very hard.

The proposed approach is based on dividing phenomena attributing accelerations due to the cinematic and position of the vehicle from the vibrations. This approach emphasis the necessity to recreate realistic configurations of the environment in order to reproduce phenomena such as stress, fatigue, while analytical modelling of suspensions and vibrations requires to introduce many parameters that are very difficult to be estimated. The pre-processing of simulation data from real data sample, allows to tune the influence of all boundary conditions and to match the technical characteristics of the simulation infrastructure. The authors are working on additional developments for extending the database as well as for conducting researches on different kind of port cranes and terminal.

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**Agostino G. Bruzzone** since 1991, he has taught "Theories and Techniques of Automatic Control" and in 1992 he has become a member of the industrial simulation work group at the ITIM University of Genoa; currently he is Full Professor in DIPTEM.

He has utilized extensively simulation techniques in harbor terminals, maritime trading and sailboat racing sectors. He has been actively involved in the scientific community from several years and served as Director of the McLeod Institute of Simulation Science (MISS), Associate Vice-President and Member of the Board of the SCS (Society for Modelling & Simulation international), President of the Liophant Simulation, VicePresident of MIMOS (Movimento Italiano di Simulazione) and Italian Point of Contact for the ISAG (International Simulation Advisory Grouyp) and Sim-Serv. e has written more than 150 scientific papers in addition to technical and professional reports in partnerships with major companies (i.e. IBM, Fiat Group, Contship, Solvay) and agencies (i.e. Italian Navy, NASA, National Center for Simulation, US Army).

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