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# Overhead crane subjected to impulse loading

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# Overhead crane subjected to impulse loading

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**Abstract**. Overhead cranes are machines designed to lift and transport heavy equipment and materials. For this reason, their design is regulated by rigorous standards (for example, the series EN13000 in Europe). However, the standards do not take into account the effect of cyclic loading due to, for example, rapid successions of short commands to place heavy machines and structures in a required position. Therefore, the aim of this research is to study the structural effect of rapid successions of command impulses. The preliminary results show that the displacement of the structure over time increases when the command impulses have a frequency equal or close to the natural frequency of the structure.

## 1. Introduction

The hoisting machines are used to lift and transport heavy equipment and materials. They are typically used to assemble apparatuses and machines, or to load and unload freights. Examples of hoisting machines are mobile and fixed cranes, overhead cranes, aerial working platforms, just to mention a few. Their load capacity varies from hundreds of N, as in lifting gears for tasks performed manually, to MN, as in cranes used to move containers up to 5 MN (shipyards or industrial installations) or heavy vessels up to 50 MN (petrochemical industry or nuclear installations). When an extremely high-load capacity is required, cranes can be used in tandem.

The design of such machines has to comply with regulations. For example, the EN 13000 is a European standard for the design, construction, maintenance, and testing of mobile cranes. The loading conditions regulated by the standards comprise the effect of several factors, such as environmental (for example, wind, snow, and ice), or due to the motion of the load, the machine itself or its parts. Among the environmental factors, in order to assess correctly the effect of wind, it is necessary to estimate accurately how it varies with time and is coupled with the dynamic behaviour of the machine.

However, the maximum load acting on the structure of a crane is not the maximum nominal load (the working load limit), but a load 1.2-2 times greater because of the dynamic effect of several factors, for example the hoisting speed, or the stiffness of the structure itself [1,2]. This is also true for all the variable phenomena. For example, the stresses induced in a tower crane by variable winds are greater than those calculated when the winds are modelled as constant [3,4,5].

**Figure 1.** Examples of cranes during positioning operations.

The standards establish that structures should be tested by cyclic loads, but only to study their response to fatigue, not their dynamic behaviour. However, cyclic loading is a common occurrence either during the assembly of heavy machines and structures, or in offshore cranes. In the first case, this happens when the part, for example a reinforced-concrete panel or a girder, has to be placed inside a structure, because the right position and orientation are usually reached by a succession of short displacements (figure 1). In the second case, loads moved by cranes installed on ships or offshore platforms are forced to oscillate by the wave motion. In both these situations, the cyclic loading could negatively affect the behaviour of the crane, because it could induce either vibrations or deviations of the load position due to the superposition of elastic responses to successive displacements.

Therefore, the aim of this paper is to determine how the behaviour of overhead cranes is affected by sequences of short displacements (or command impulses), notably their distribution in time.

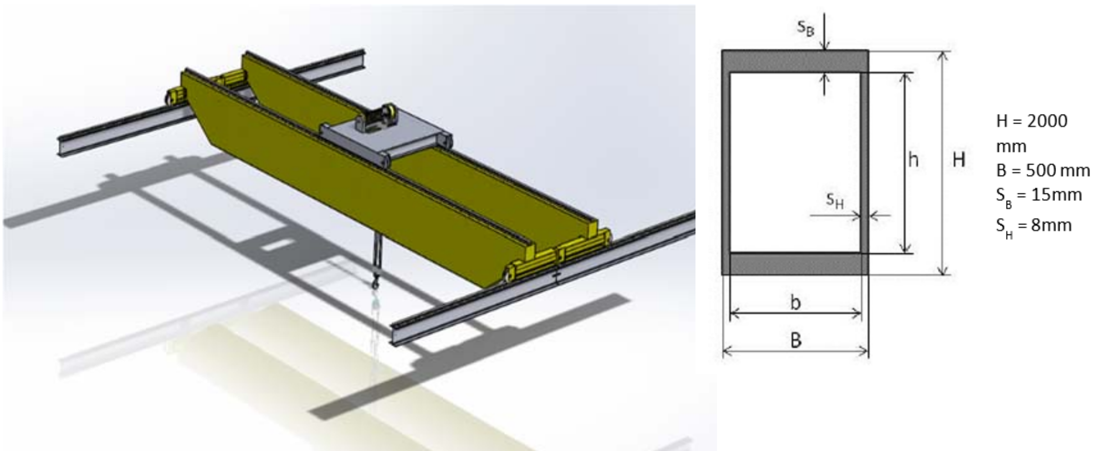



**Figure 2.** The solid model of the crane (left), and the section of the girder (right).

## 2. Numerical analysis

An overhead crane was designed with the following features (figure 2): two box girders, 50 tonnes of nominal load, a span of 20 m.

The structural dimensioning was performed by analytic methods. The girder section was 2000x500 mm, while the thickness was 15 mm in the horizontal plates and 8 mm in the lateral ones. Inside the girder, stiffening elements with a thickness of 5 mm were inserted to avert instability problems. Then, a finite elements analysis was performed with Autodesk Simulation® on a model of the crane designed with SolidWorks®: the model had bricks elements with quadratic formulation, and a total of about 2.5 $10^6$ degrees of freedom. The numerical analysis was carried out on one girder, constraining both the extremities as hinges, and applying the maximum load in the middle of the span. Figure 3 shows the resultant displacement of the crane.

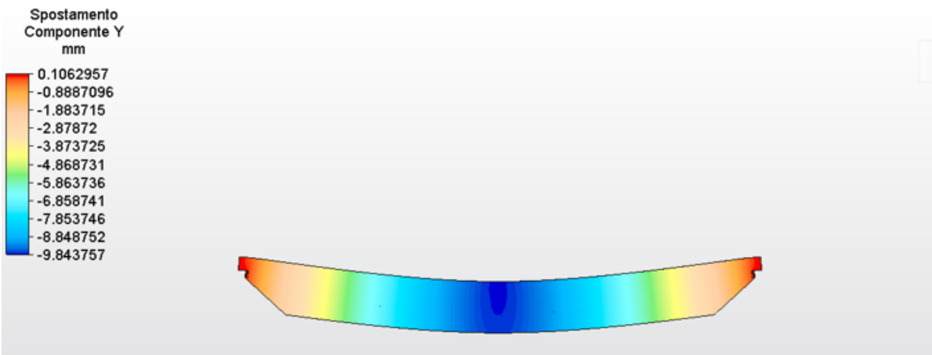



**Figure 3.** The vertical displacement when the maximum load is at the middle of the crane.

After a structural analysis conducted according to the standards, the following step was the dynamic evaluation of the crane [10]. Figure 4 shows the deformation of the structure at the first three vibrational modes, while table 1 lists the first natural frequencies and the corresponding modal participation coefficients. The predominant vibrational mode was the third (which could also be found analytically by the modal determination method [11, 12]), although the ninth and seventeenth modes had appreciable values as well. The natural frequencies were typical of lifting machines.

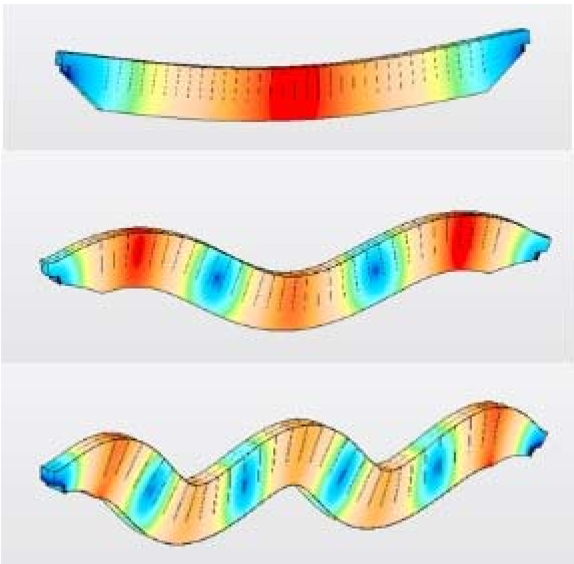


**Figure 4.** Shapes of the first vibrational modes.

A key factor in dynamic analyses is the correct calculation of the damping coefficient, which depends on both the material and the structure, especially if the structure is welded or bolted. In general, the damping coefficient has a value that is 4-10% of the value of the critical damping. In [2], the result of accelerometric tests on a lifting platform is reported: the damping coefficient estimated by the logarithmic decrement method was 8%. In this study, a damping coefficient value equal to 5% of the critical damping was used, because the lifting machine was different (the components number that make up the machine are less) and with this assumption the numerical displacement estimation was higher.

**Table 1.** Natural frequencies and modal partecipation coefficients of the girder.

| Mode | Freq. (Hz) | Modal eff. (Weight) | Mass % | Cumulative (Weight) | Mass % | Partecipat. Factor |
|---|---|---|---|---|---|---|
| 1 | 2.06e-4 | 0 | 0 | 0 | 0 | 0 |
| 2 | 7.87e+0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 1.60e+1 | 6.40e+4 | 82.59 | 6.40e+4 | 82.59 | 2.55e+0 |
| 4 | 2.31e+1 | 0 | 0 | 6.40e+4 | 82.59 | 0 |
| 5 | 4.61e+1 | 0 | 0 | 6.40e+4 | 82.59 | 0 |
| 6 | 5.45e+1 | 0 | 0 | 6.40e+4 | 82.59 | 0 |
| 7 | 5.49e+1 | 0 | 0 | 6.40e+4 | 82.59 | 0 |
| 8 | 7.79e+1 | 0 | 0 | 6.40e+4 | 52.59 | 0 |
| 9 | 1.08e+2 | 6.76e+3 | 8.73 | 7.08e+4 | 91.32 | 8.30e-1 |
| 10 | 1.12e+2 | 2.65e+0 | 0 | 7.08e+4 | 91.32 | 1.64e-2 |
| 11 | 1.16e+2 | 0 | 0 | 7.08e+4 | 91.32 | 0 |
| 12 | 1.29e+2 | 1.139e+2 | 0.15 | 7.09e+4 | 91.47 | 1.077e-1 |
| 13 | 1.61e+2 | 0 | 0 | 7.09e+4 | 91.47 | 0 |
| 14 | 1.69e+2 | 0 | 0 | 7.09e+4 | 91.47 | 0 |
| 15 | 1.76e+2 | 0 | 0 | 7.09e+4 | 91.47 | 0 |
| 16 | 2.11e+2 | 0 | 0 | 7.09e+4 | 91.47 | 0 |
| 17 | 2.35e+2 | 2.077e+3 | 2.68 | 7.30e+4 | 94.15 | 4.60e-1 |
| 18 | 2.42e+2 | 0 | 0 | 7.30e+4 | 94.15 | 0 |
| 19 | 2.55e+2 | 0 | 0 | 7.30e+4 | 94.15 | 0 |
| 20 | 2.63e+2 | 0 | 0 | 7.30e+4 | 94.15 | 0 |

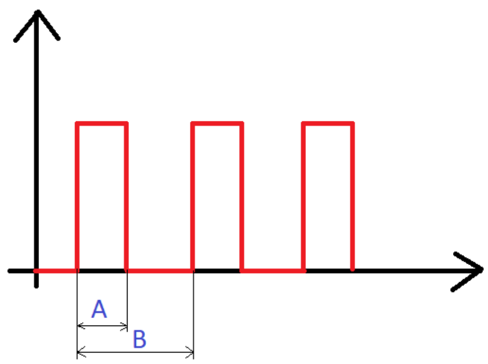



**Figure 5.** Train of pulses as displacement commands: A is the duration of the pulse; B is the time interval between two successive pulses.

## 3. The cyclic loading

The cyclic loading was set as trains of impulses: the duration of the impulses was fixed to 0.1 s, but their frequency was variable from test to test (in figure 5, parameters A and B, respectively). Such choice is arbitrary, because the phenomenon is random and its exact definition required a long experimentation and more complex solving techniques [13]. In addition, it should be studied how the transmission chain from the motor to the hook affects the motion of the load. However, this research is only a preliminary study of the effect of repeated loading on lifting equipment, therefore it is acceptable to leave out complex phenomena, such as the effect of blast loading on the properties of the material [14], or the damage of structure subjected to impulse loading [15]. Figure 5 shows the train of impulses applied to the hoist to simulate a succession of displacement commands: A is the duration of the impulse, while B is the time interval between two successive impulses. The duration A was fixed to 0.1 s, while the time interval B was set in a range of 0.8-0.15 s. The 0.1 s value was chosen because it is the reasonable minimum value for the operator that acting on the start command for move the load.

The numerical solution with finite elements can be computed either by modal superposition or by direct integration [12, 15]. In this study, the modal superposition method was used, but only after the principal variables of both methods were calculated to ensure a converged solution. The first twenty natural frequencies was included, which amounted to more than 90% of the total mass.

## 4. The results

Figure 6 shows the maximum displacement of the middle of the girder over time with different values of impulse duration A and time interval B (figure 5).

However, overhead cranes can be fitted with electric equipment for supplying and controlling the crane and the trolley. This equipment adds a significant weight to the structure, and it is usually positioned inside the boxed girders. In this study, a weight of 3000 N was added in the middle of the girder. The amount of the added weight was equal to the weight of the equipment fitted in an actual crane with equivalent characteristics. Table 2 shows the first natural frequencies and partecipation factors. As expected, the fundamental frequency in the vertical plane had a modal participation coefficient greater than in table 1.

Figure 7 shows the dynamic response of the crane with the additional weight for different combinations of impulse duration A and time interval B.

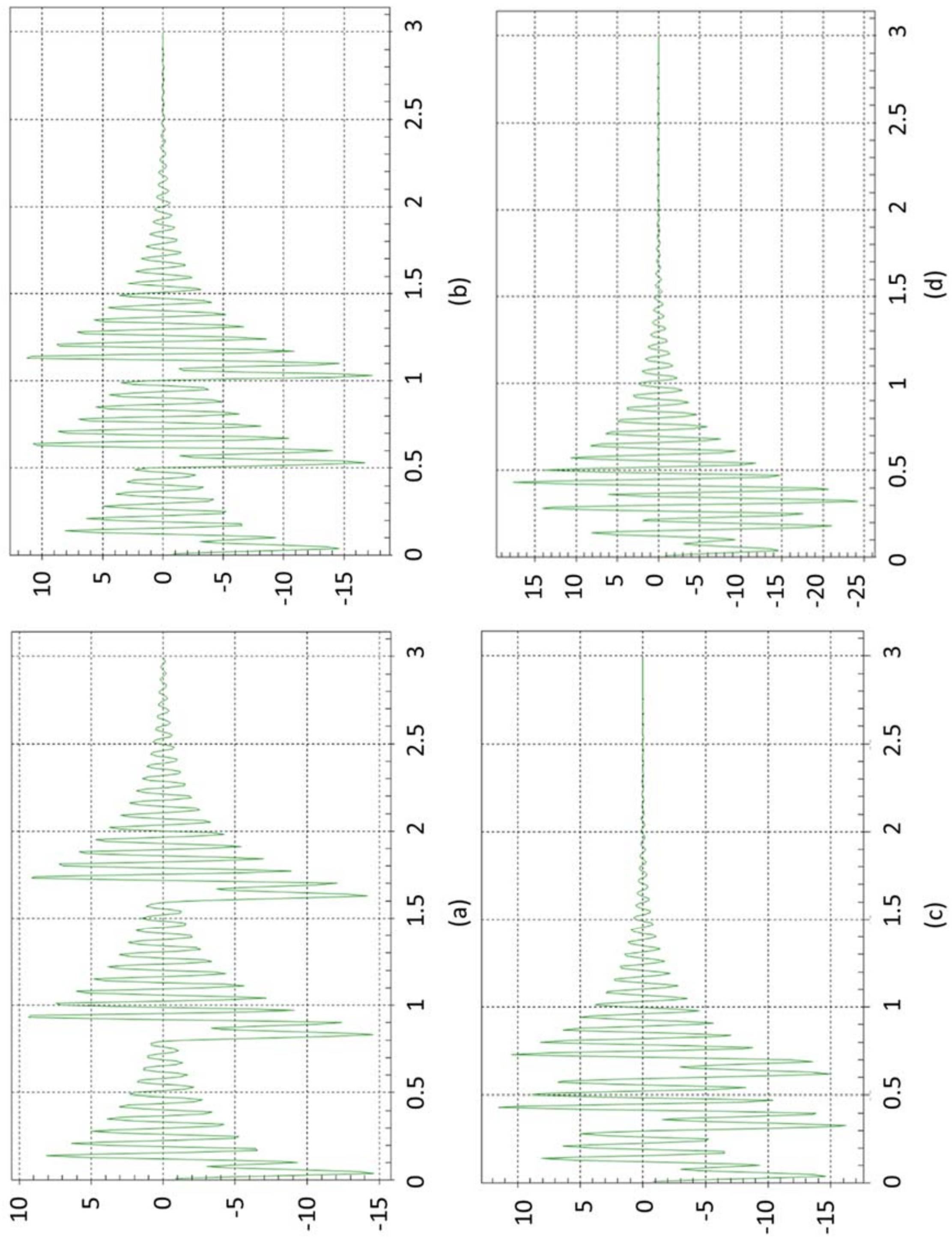



**Figure 6.** Maximum displacement over time for various combinations of impulse duration A and time interval B: (a) A = 0.1 s, B = 0.8 s; (b) A = 0.1 s, B = 0.5 s; (c) A = 0.1 s, B = 0.3 s; (d) A = 0.1 s, B = 0.15 s (y-axis displacement [mm]; x-axis time [s]).

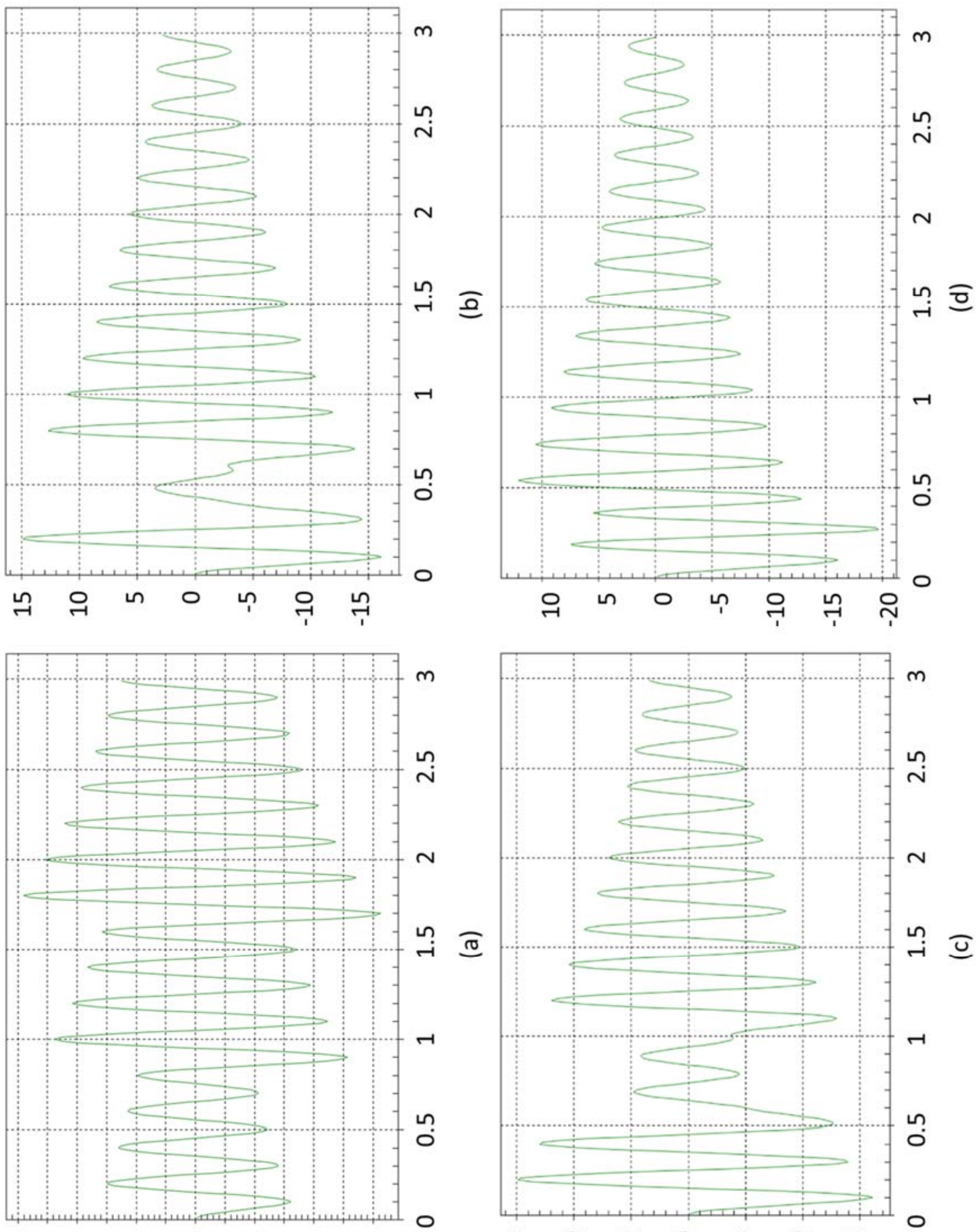



**Figure 7.** Maximum displacement over time of the girder with additional weight for various combinations of impulse duration A and time interval B: (a) A = 0.1 s, B = 0.8 s; (b) A = 0.1 s, B = 0.5 s; (c) A = 0.1 s, B = 0.3 s; (d) A = 0.1 s, B = 0.15 s (y-axis displacement [mm]; x-axis time [s]).

**Table 2.** Natural frequencies and modal partecipation coefficients of the girder with additional weight.

| Mode | Freq. (Hz) | Modal eff. (Weight) | Mass % | Cumulative (Weight) | Mass % | Partecipat. Factor |
|---|---|---|---|---|---|---|
| 1 | 1.07e-4 | 0 | 0 | 0 | 0 | 0 |
| 2 | 2.38e+0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 5.09e+0 | 4.14e+5 | 96.05 | 4.14e+5 | 96.05 | 6.49e+0 |
| 4 | 2.31e+1 | 0 | 0 | 4.14e+5 | 96.05 | 0 |
| 5 | 2.78e+1 | 0 | 0 | 4.14e+5 | 96.05 | 0 |
| 6 | 5.14e+1 | 1.33e+1 | 0 | 4.14e+5 | 96.05 | 3.69e-2 |
| 7 | 5.19e+1 | 0 | 0 | 4.14e+5 | 96.05 | 0 |
| 8 | 7.35e+1 | 8.46e+3 | 1.96 | 4.22e+5 | 98.01 | 9.28e-1 |
| 9 | 7.74e+1 | 0 | 0 | 4.22e+5 | 98.01 | 0 |
| 10 | 9.50e+1 | 0 | 0 | 4.22e+5 | 98.01 | 0 |
| 11 | 1.05e+2 | 0 | 0 | 4.22e+5 | 98.01 | 0 |
| 12 | 1.12e+2 | 0 | 0 | 4.22e+5 | 98.01 | 0 |
| 13 | 1.29e+2 | 1.08e+2 | 0.03 | 4.23e+5 | 98.03 | 1.04e-1 |
| 14 | 1.49e+2 | 0 | 0 | 4.23e+5 | 98.03 | 0 |
| 15 | 1.56e+2 | 2.67e+0 | 0 | 4.23e+5 | 98.04 | 1.63e-2 |
| 16 | 1.69e+2 | 1.55e+3 | 0.59 | 4.25e+5 | 98.63 | 5.098e-1 |
| 17 | 1.75e+2 | 1.42e+2 | 0.03 | 4.25e+5 | 98.66 | 1.20e-1 |
| 18 | 1.76e+2 | 2.56e+2 | 0.06 | 4.26e+5 | 98.72 | 1.61e-1 |
| 19 | 1.84e+2 | 2.02e+1 | 0 | 4.26e+5 | 98.72 | 4.54e-2 |
| 20 | 1.93e+2 | 0 | 0 | 4.26e+5 | 98.72 | 0 |

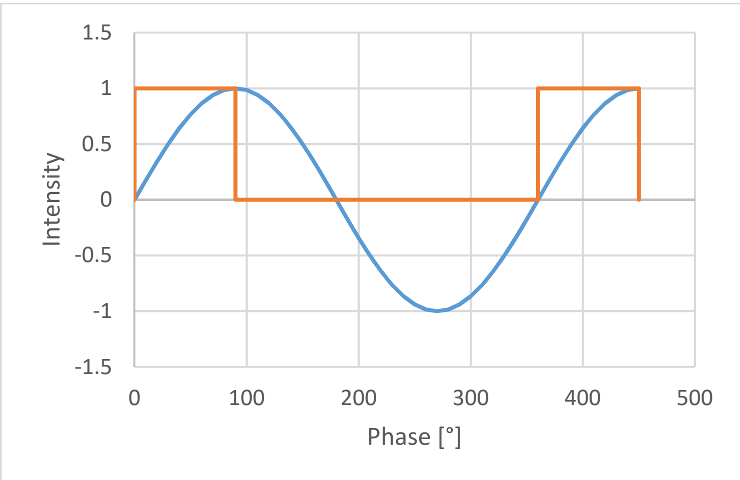
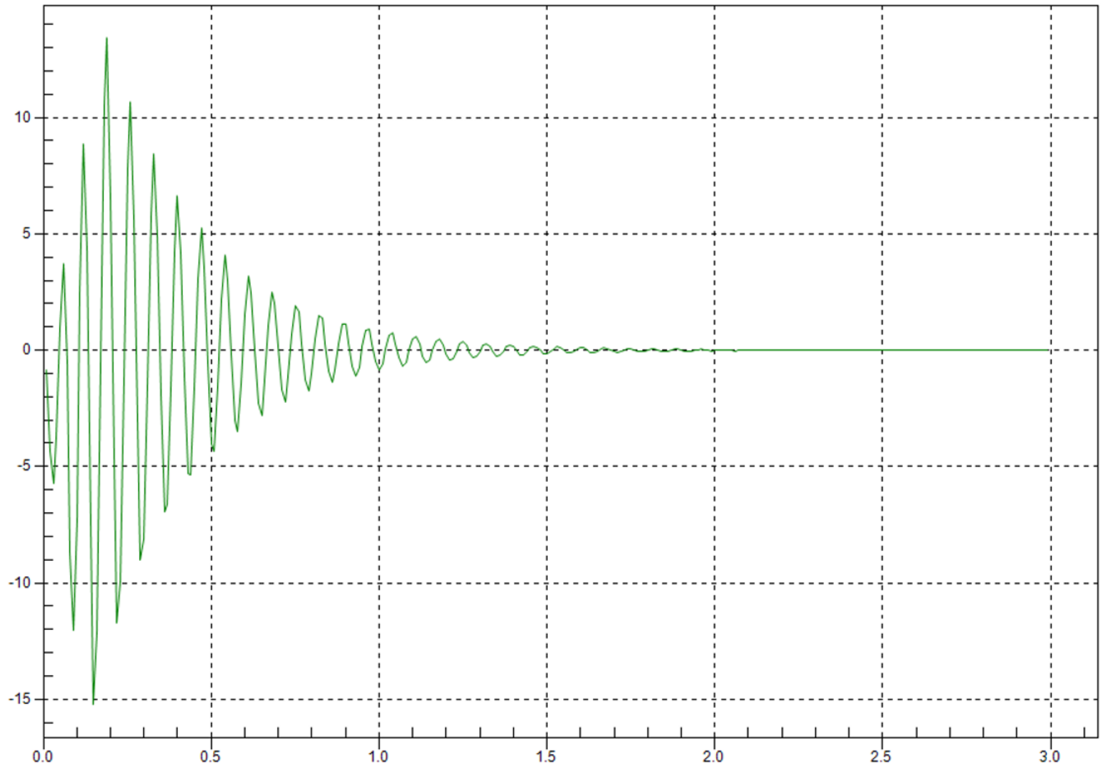
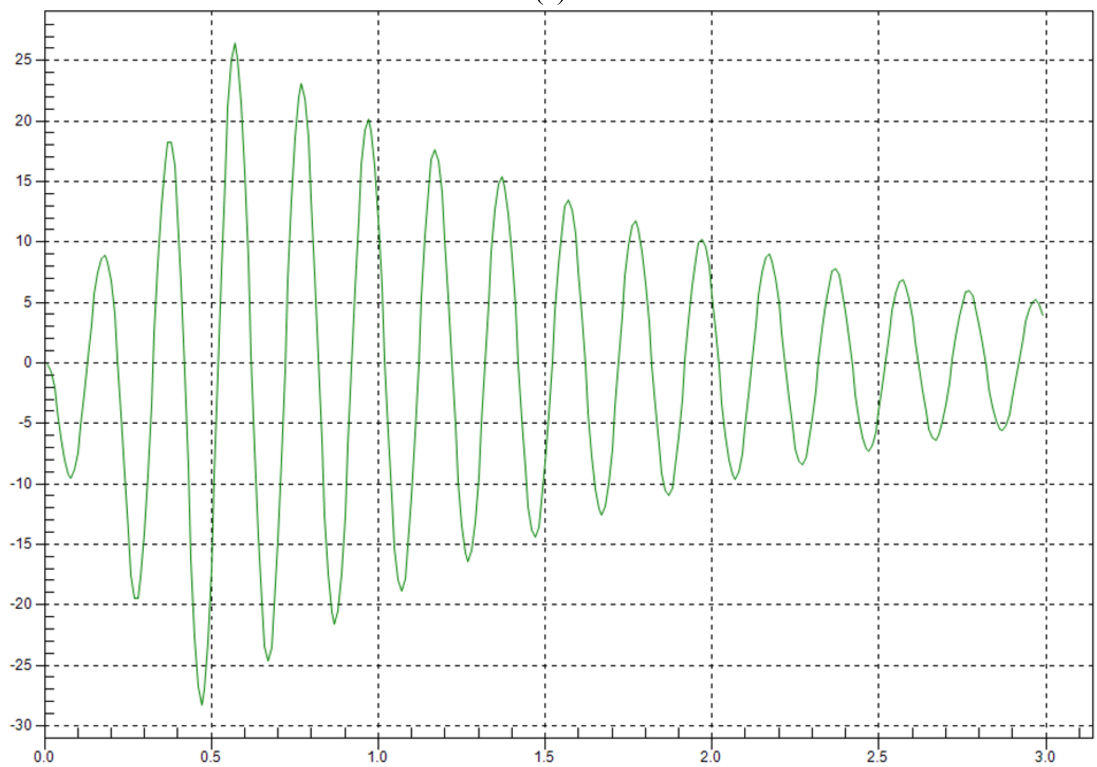



**Figure 8.** Blue line: generic structure displacement, red line: external action applied to the structure.




(a)




(b)

**Figure 9.** Maximum displacement over time: (a) A = 0.0155 s, B=0.062 s; (b) A = 0.049 s, B=0.196 s (y-axis displacement [mm]; x-axis time [s]).

## 5. Discussion

When a succession of three command impulses was applied, the behaviour of the structure was strongly influenced by the load. However, figure 6(d) shows that the maximum displacement increased at each impulse for a specific combination of duration A and time interval B. Therefore, further analyses were performed in order to correlate A and B to the crane natural frequency in the vertical plane. These new preliminary analyses showed that the maximum displacement was obtained by the command sequence shown in figure 8, in which the duration A and the time interval B were respectively 1/4 of and equal to the period of the natural frequency. Figure 9 shows the maximum displacement with the new sequence.

## 6. Conclusion

The aim of this research was to study how a succession of command impulses affects the behaviour of overhead cranes. Successions of command impulses are especially used during the positioning of heavy components. The effect was studied by the numerical model of an actual crane with a maximum loading of 50 tonnes.

The results showed the maximum displacement increase due to the dynamic instability if the duration of the impulses and their spacing are correlated to the natural frequency of the structure.

However, this result is only preliminary to further steps, which are required to study accurately the dynamic behaviour of cranes, such as to take into account the effect of actual impulse waveforms and close modal participation factors, as well as their interrelation with the damping factors of material and structure.

Given that specific combinations of duration and spacing of the command impulses amplify the displacements of the structure, it is advisable that the controlling unit of the crane could avoid such combinations to avert the danger of excessive stresses and local/global instabilities, especially in telescopic cranes. For this reason, the next step of this research will be to study different hoisting machines, because it is our opinion that, in designing and testing such machines, the standards should take into account the dynamic and structural effect of successions of command impulses.

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