High Rise Elevators – Challenges and Solutions in Ride Comfort Simulations

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***Abstract**: The megatrend of urbanization requires the development of cities on vertical, which brings new challenges for the elevator industry. For buildings in the range of 500 – 1000 meters height, there are several technical issues to tackle, such as ride comfort and safety in case of earthquakes or strong winds, besides the people flow logistics.*

This presentation is focused on in-car vibrations and shows how KONE uses ABAQUS in the chain of multi-physic computation. The ride comfort depends on the elevator design, running parameters, installation quality and the building behavior. From finite element point of view the important issues that induce guide rails variable movement are: misalignment of the guide rails which typically are in the range of millimeters with a 10 cm distance between the peaks and lengths over 500 meters, suspension, compensating and travelling ropes introducing variable mass acting on the sling as a function of car position, air-flow induced forces caused by the counterweight passage at high speed and sway shape and magnitude of the building.

Therefore, special user defined elements have been developed to include guide rail geometry and movements as well as the variable mass of the ropes. The advantage of this approach is that the elevators dynamics and stresses/displacements for the entire structure can be analyzed for every elevator component for the entire travel, such as: car, sling, roller guides and roller stopper.

***Keywords**: Elevators, Vibrations, Ride comfort, Sway, User element, Substructures.*

1. Introduction

In the recent past, elevator ride comfort has been receiving increasing attention from building constructors, elevator users and manufacturers. Ride comfort includes smooth ride and landing, levels of vibrations and noise inside the car, temperature, smell, spaciousness; the entire perception of the users from stepping in, till stepping out of the elevator.

For high and mega-high buildings, in addition to the traditional factors influencing ride comfort (Simbierowicz, 2013), the bad weather or earthquakes can lead to large movements of the buildings, that have a flexible design in order to sustain such loads. These movements induce severe loads on elevator components installed in the shaft - the vertical passageway where the elevator is installed. In several articles (Benosman, 2015), (Miura, 2012), (Wranabe, 2012) the dynamics of the ropes for sway conditions were studied and analytical models were developed in order to understand their effect on car vibrations. However the impact of the building sway on the guide rails on which the cars are running, were not included in the calculation. In this paper a multi-physics model was developed, in order to compute the car vibrations as a function of: sway of guide rails, sway of ropes, air-flow loads, installation quality of the guide rails, car components and running parameters as speed, jerk and acceleration. The study case is a double deck elevator, consisting in two cars, running with 10 m/s.

This approach allow KONE, one of the design leaders in the elevator industry, to predict the ride comfort for different sway conditions and provide efficient solutions for smooth people flow in the building.

2. The architecture of the model

For the last 100 years most of the improvements of the ride comfort for low and middle rise buildings have been done by trial and error methods. Several prototypes were built and their components were improved and developed until the targets were reached. In case of mega-high rise buildings, the number of elevators with the same dimensions is very few; therefore each case is the “prototype”. For this reason simulation is the only solution to predict and improve the ride comfort of the elevators in mega-high buildings. The ride comfort is analyzed using ABAQUS/Standard with a dynamic approach following the car travel for more than 500 meters, which takes more than 60 seconds. A mixture of beam elements and substructures were chosen to have a reasonable model size containing more than 1 M degrees of freedom (Mdof). This makes it possible to cover all the factors influencing car vibrations as shaft dimensions, guide rails structure and misalignments, roller guides, sling, car, counterweight, suspension, compensating and travelling ropes.

The finite element (FE) model contains 17 substructures. Each substructure has been defined by both static and dynamic modes where the later have been defined from a frequency analysis using all modes up to 80 Hz.

2.1 Guide rails

The guide rails fixed on shaft walls are the equivalent of train tracks and they are restricting the horizontal movements of the cars. The length of the guide rails may reach over 500 meters, therefore they need to be installed as separate components fixed by fish plates one from another and through brackets to the walls. The fixing components are inducing changes in the guide rail stiffness and also transmit the building sway movement to the car. Due to extensive length of the guide rails, the manufacturing tolerances and the installation quality induce misalignments in order of fractions of millimeters for the entire travel with a peak to peak distance with the order of 100 mm. These misalignments were proved to be the main factor influencing on the ride comfort, therefore they need to be modeled with high accuracy. The guide rails, the fish plates and the brackets were modeled using beam elements and the misalignments were implemented by using user defined elements. The misalignments of the guide rails were measured for specific elevators and were implemented as excitations to the user elements (Figure 2-1). The building sway was computed based on architectures evaluation for specific building shape, height and statistical weather conditions and applied either as excitations to the user elements or by boundary conditions for the brackets.

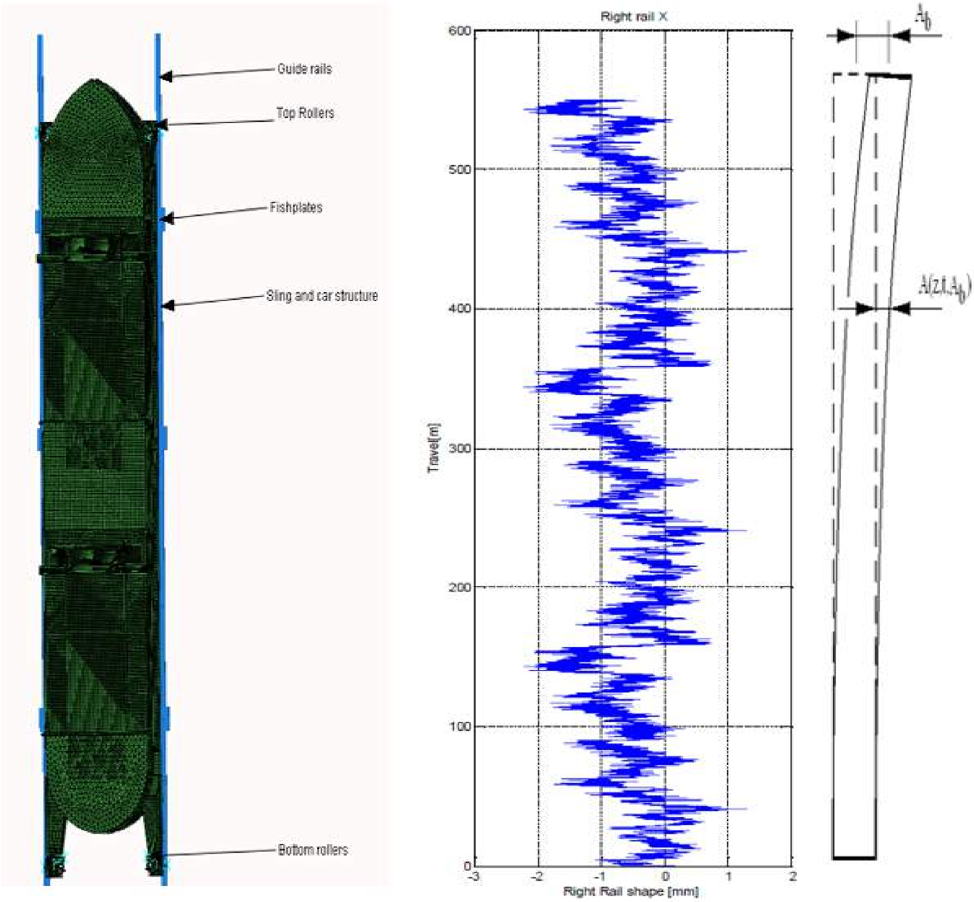

Figure 2-1 Elevator structure and example of measured misalignment of the guide rails applied as excitations on the model and also the movement of the guide rail due to building sway.

2.2 Roller guides

The roller guides are the part of the system in contact with the guide rails. Their role is to isolate and damp the excitations induced by the guide rails and to restrict the car movement. Each roller guide was modeled using mainly solid elements and then condensed to four substructures. The roller guides also has levers used to pre-stress the roller guide wheels. Since the levers have rotational degrees of freedom they can't be part of the roller guide substructure and thus three more substructures are added for each roller guide (Figure 2-2). The roller wheels are assumed to be always in contact with the corresponding guide rail and a low coefficient of friction. To simplify the analysis the roller wheels are assumed not to rotate and instead glide along the guide rail. This simplification has been necessary, since the non-linear rolling effect would have been negligible inside the substructure, where the entire behavior is linearized. In order to minimize the effects of this simplification, the rubber material of the wheels, was modeled based on tested dynamic behavior of roller guide - guide rails interaction. The interaction between the roller wheel and the guide rail is defined by user defined elements.

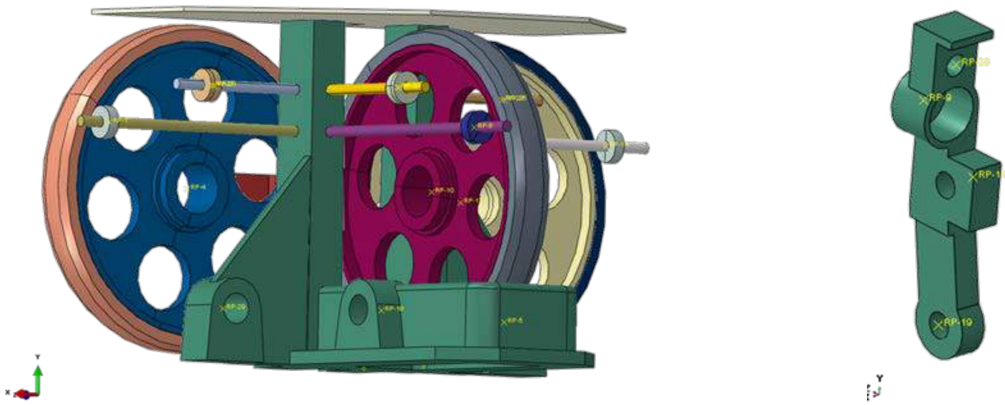

Figure 2-2 Roller guide substructure (on the left) containing 3 separate lever substructures (on the right).

Due to their faster computation abilities, connector elements are used to define: stoppers limiting the rotation of the levers; pretension of the wheels and contact between the wheels and guide rails. Stoppers are defined by two connections: one for the soft rubber contact and one for the steel hard contact. The contact between the wheels and guide rails is ensured by pre-tensioned springs modeled also by connectors. Finally the interaction between guide rails and rubber wheels is defined by a connector. Since each roller guide contains three wheels there will be 15 connector elements for each roller which are defined on the global level. For each roller guide, retained nodes are used to define: contact with the guide rail; attachments to the sling and levels and also connector elements, totally 41 retained nodes.

2.3 Sling and cars

The sling is the stiff component that is attached to the suspension, compensating and travelling ropes. The active mass of compensating and travelling ropes attached at the bottom of the sling, vary with the position of the sling in the shaft.

The cars are fixed through flexible connections inside the sling. Since the passengers are positioned inside the car and they perceive the vibrations due to their contact with the floor of the car, the output of the computation is the acceleration of the floor in three directions, filtered with a low pass Butterworth filter, in order to simulate the human perception.

The cars and sling are shown in Figure 2-3.

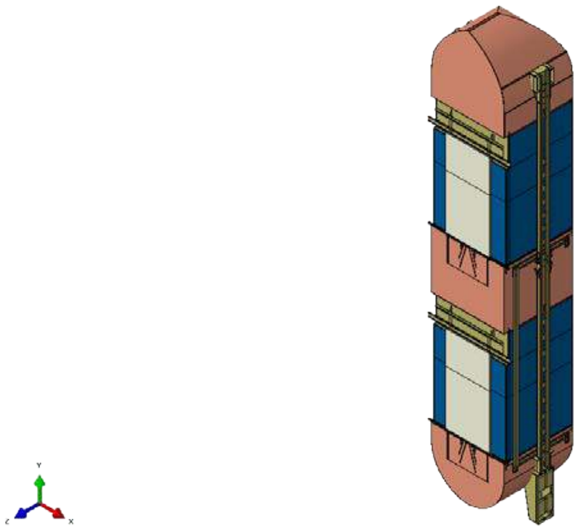

Figure 2-3 Cars and sling (double deck).

The cars and sling were modeled using solids, shells, beams and springs. The suspension ropes were modeled as variable loads (Figure 2-4) function of the sling position in the shaft and building sway and computed using a finite difference model. The active variable mass of the compensating and travelling ropes were then calculated by applying variable gravity load on the corresponding user defined element (Figure 2-5). The car and sling substructure contains retained nodes for attachment of the roller guides and also attachment nodes for the compensating and suspension ropes. Also a few nodes at each floor are retained making it possible to have output required for calculating the ride comfort and for possibilities to place passengers at different positions. Furthermore, surfaces for applying air-flow loads which are used to define unity load cases were selected.

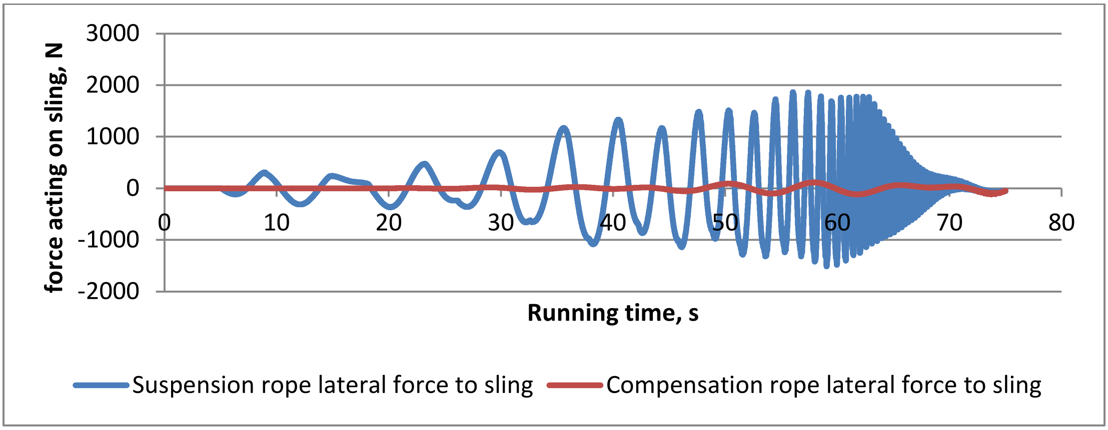

Figure 2-4 Loads, applied on the sling, modeling the impact of suspension and compensating ropes due to the sway of the building.

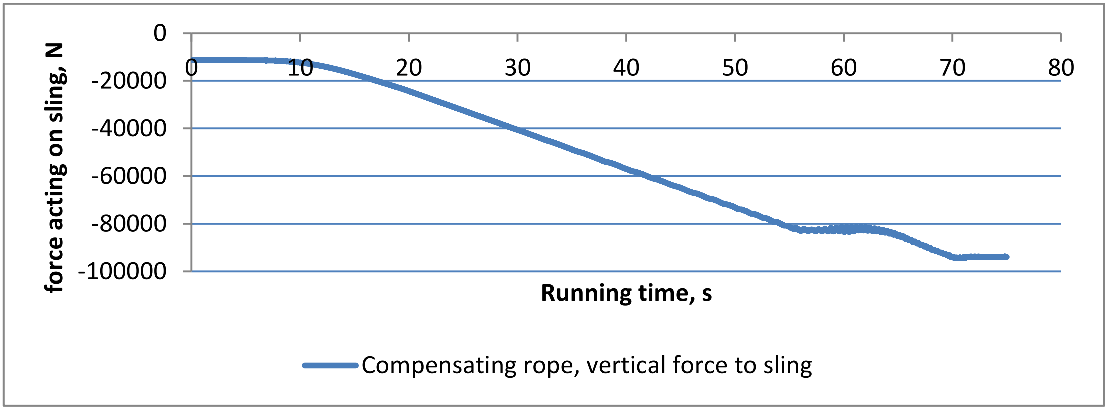

Figure 2-5 Loads, applied on the sling, modeling the impact of suspension and compensating ropes due to the sway of the building.

2.4 Counterweight

The ride comfort class of the elevator is defined as a time variation of the acceleration magnitude which is alternatively greater or smaller than a reference level (Howkins, 2006). Therefore it is enough that one excitation causes a singular higher peak to destroy the smoothness of the ride. For this reason the air-flow loads induced by the counterweight passing by at speeds higher than 10 m/s cannot be ignored. The air-flow loads were computed using a transient Computational Fluid Dynamics (CFD) code (Figure 2-6) and the calculated loads were applied on the car walls in the FE model. The CFD loads are calculated for a travelling speed of 10 m/s and only for the time window close to when the counterweight is passing the car and sling. Thus the time dependent amplitude curves have to be transformed to the actual speed used at the simulation.

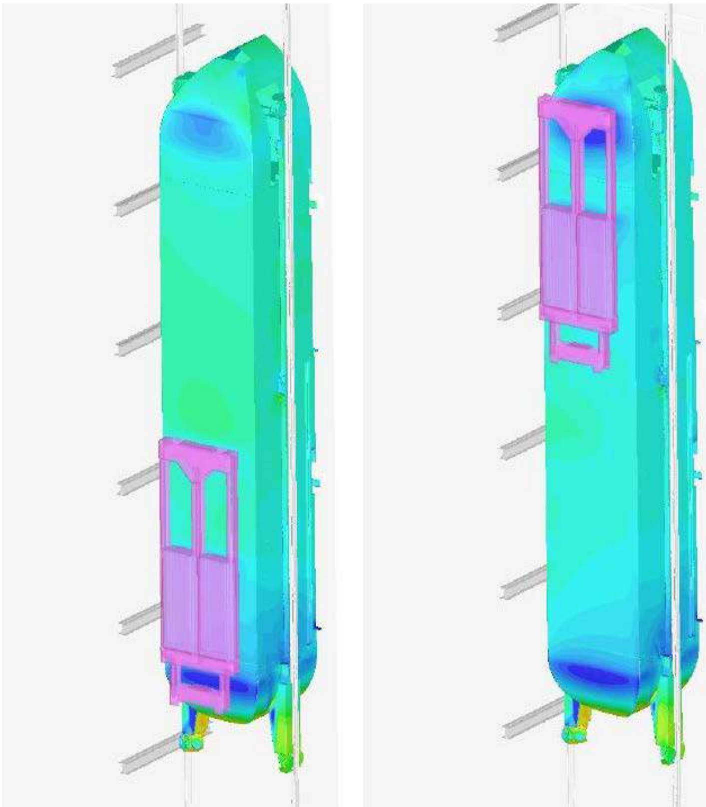

Figure 2-6 Air-flow loads due to passing of counterweight (pink) computed with transient CFD.

3. User defined element

The user defined elements for connecting each roller guide to the corresponding guide rail contain three nodes – two being the nodes defining each beam element and the third node being the roller guide attachment node (Point A, B, C, see Figure 3-1). This means that for each roller guide the numbers of user defined elements are equal to the number of elements of each guide rail. During the car travel the code detects which element is active and also the corresponding misalignment value (two translations and one rotation) by linear interpolation between the current position and the position of the closest measurement data.

The values of misalignments where measured in an existing site and extrapolated for longer guide rails.

The misalignments are then added to the guide rail displacement within the user defined subroutine used by the user defined elements. The brackets, fixing the guide rails to the shaft's walls are modeled as springs with pre-computed stiffness in three directions. One node is on the guide rail, one on the shaft. The sway of the building is defined by position and time dependent prescribed displacements at the bracket node located on the shaft. For each bracket node the corresponding amplitude function is defined by a Python script.

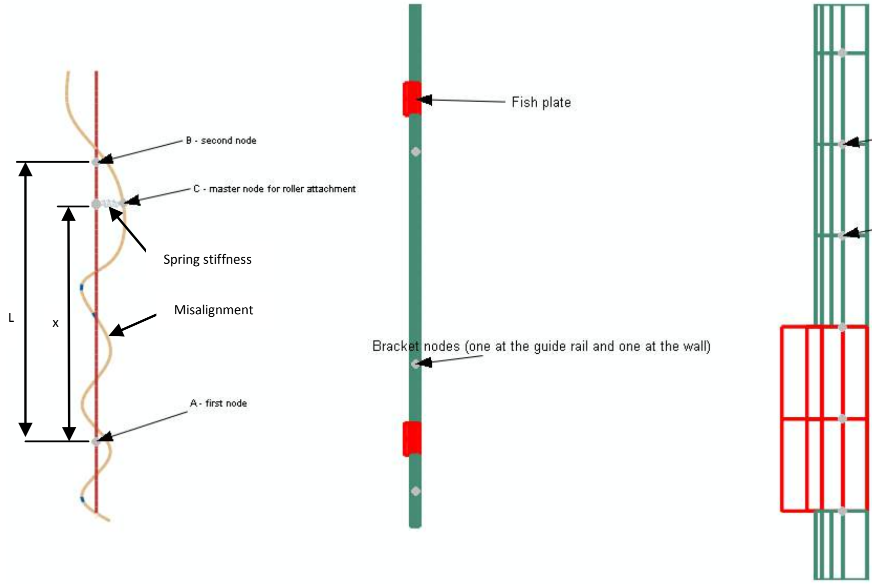

Figure 3-1 Notations for the user defined element.

Coding of the user defined element is based on equations for equilibrium. With F denoting the force at each node, the equations for translational degrees of freedom are:

$$F_A + F_B + F_C = 0$$

$$F_C * X + F_B * L = 0$$

The position of the attachment node for the roller guide is defined as $R=X/L$.

Adding a spring with stiffness k, the force at the roller guide attachment node is:

$F_C=k*(U_C-(U_A+U_B*R+\alpha))$, where α is the misalignment, which implies:

$$\begin{Bmatrix} F_A + \alpha * k * (R-1) \\ F_B - \alpha * k * R \\ F_C + \alpha * k \end{Bmatrix} = k * \begin{pmatrix} (R-1)^2 & -R*(R-1) & (R-1) \\ -R*(R-1) & R^2 & -R \\ (R-1) & -R & 1 \end{pmatrix} \begin{Bmatrix} U_A \\ U_B \\ U_C \end{Bmatrix}.$$

With M denoting the torsion moment at each node, $\Delta\varphi$ (the rotational misalignment) the equations for rotational degrees of freedom are:

$$M_A+M_B+M_C=0$$

$$M_A=M_B$$

$M_C = k_\varphi * (\varphi_C - (\varphi_A + (\varphi_B + \varphi_A) * R + \Delta\varphi))$, where $k_\varphi$is an additional rotational spring.
Therefore:

$$\begin{Bmatrix} M_A - 0.5 * k_\varphi * \Delta\varphi \\ M_B - 0.5 * k_\varphi * \Delta\varphi \\ M_C \quad + k_\varphi \quad * \nabla\varphi \end{Bmatrix} = k_\varphi * \begin{pmatrix} -0.5 * (R-1) & 0.5 * R & 0.5 \\ -0.5 * (R-1) & 0.5 * R & 0.5 \\ (R-1) * \varphi_A & -R & 1 \end{pmatrix} \begin{Bmatrix} \varphi_A \\ \varphi_B \\ \varphi_C \end{Bmatrix}.$$

The user defined elements used for defining the active variable mass for compensating and suspension ropes are defined by two nodes where one node is used for attachment to the sling and the second node is used as a reference node defining the current length of the actual rope. The operator only defines the active mass matrix.

4. Results

For each analysis results as displacement, velocities, accelerations and reaction forces are saved as history output as well output variables of interest from the connector elements.

The validation of the model has been done by comparing the acceleration values computed at the center of the two decks of elevator with measured values for similar elevators. A Butterworth low pass filter of 12Hz has been applied to the results, in order to take into account the human perception; and for an easier compassion the data has been saved in gals (cm/s^2).

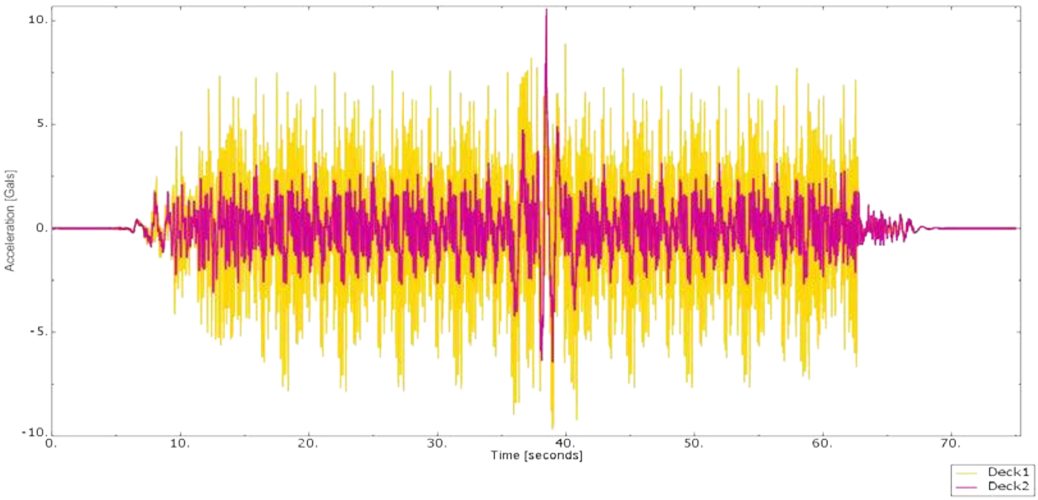

Figure 4-1 Computed acceleration at the center of the decks, for non-sway condition, upward ride.

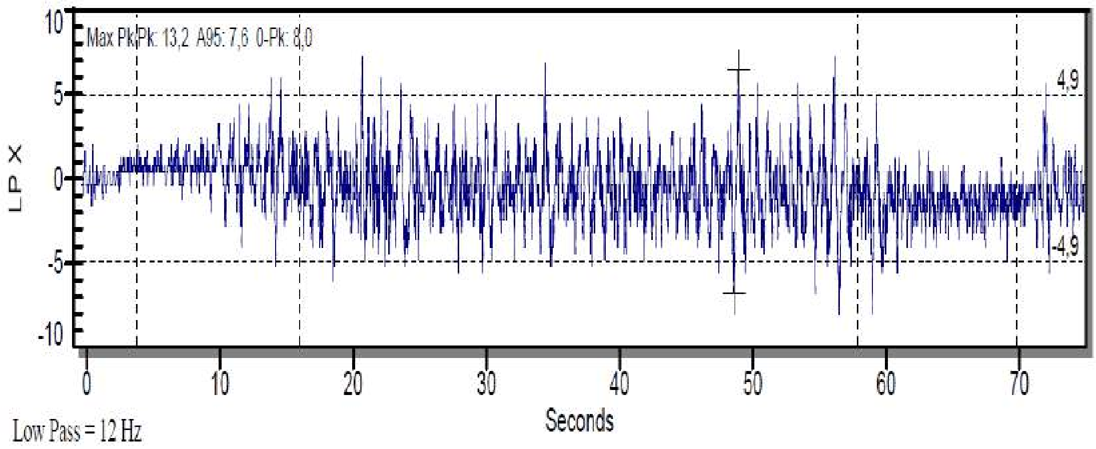

Figure 4-2 Measure acceleration at the center of the deck for non-sway condition on similar elevator.

The computed (Figure 4-1) and measured data (Figure 4-2) are in good correlation for similar elevators, therefore the model can be used for further predictions.

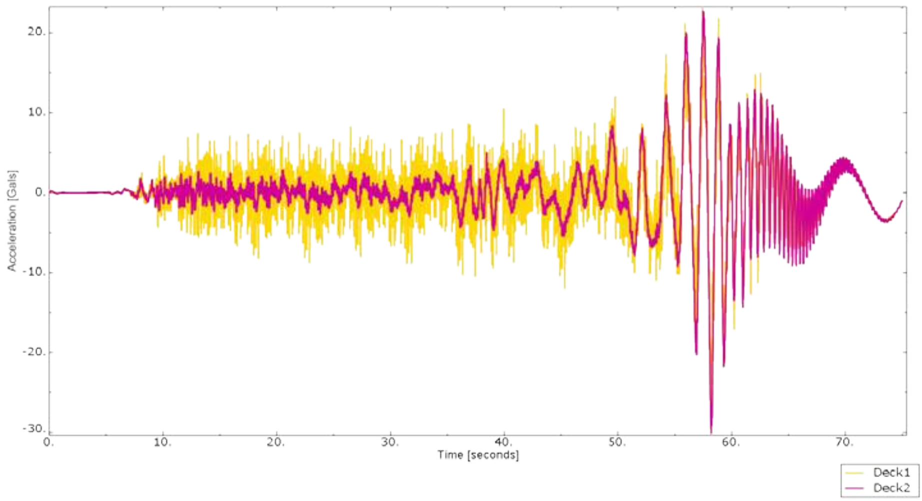

Figure 4-3 Computed acceleration at the center of the floor, for half sway of the building, upward ride.

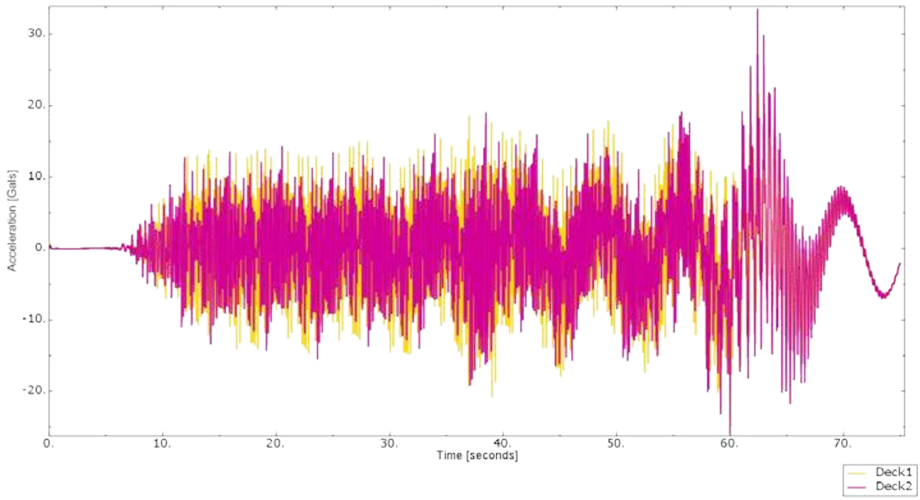

Figure 4-4 Computed acceleration at the center of the deck, for full sway of the building, upward ride.

The sway of the ropes due to bad weather condition is usually calculated for the car parked at a specific floor, or for specific running parameters of the elevator, where the sling-car-roller guide system is modeled as a point with mass and damping properties. By using FEM the designer can have a deeper understanding of the phenomena happening in the system for sway conditions. Some of the most important findings are:

- The sway of the car becomes larger and larger at the top of the building. The peak-to-peak maximum value is increasing from 19 gals, for no sway; to 53 gals for half sway and 83 gals for full sway of the building.

- By varying the design of the components, used materials and running conditions of the car, the designer is provided with a tool to improve the ride comfort of the elevator by limiting the peak-to-peak values under an acceptable level.

- This computation is critical for improving the people flow in the building during the bad weather condition, when the speed of the elevator can be optimized to ensure good ride comfort and safety travel, based on the amplitude and frequency of the building sway.

5. Conclusions

Using Abaqus/Standard for simulation of ride comfort provides valuable information such as stresses/strains for all components defining the high-rise elevator. Several features available in Abaqus, such as substructures, connections and user defined elements make the computation possible, performed in reasonable time and reliable in comparison with tested data.

Usage of substructures reduces the number of active degrees of freedom from more than 8 000 000 to approximately 50 000. Without this decrease in problem size, ride comfort simulations would be hardly performed with available computer resources. The penalties from using substructures are the linearized response and accuracy of the results depending on the number of retained eigen-modes included in the analysis. This limitation is estimated to be negligible for this simulation, because the frequency range of interest is lower than 12 Hz for in-plane vibrations and 80 Hz for vertical vibrations. Although computed for 50 kdof, the entire 8 Mdof can be evaluated by using recovery procedure offered by Abaqus. However the process is substantially slower and it should be used with care.

Modeling the misalignments of over 500 meters guide rails by geometry would be extremely difficult; however, the usage of user defined elements makes it possible and rather straightforward. In addition choosing cubic integration beam elements instead of solid elements for guide rails increase the speed of computation considerably without losing the accuracy.

Input of variable mass from ropes was automatized by coding a user defined elements. The alternative of adding manually different masses at each time increment is extremely complicated.

Summarizing, the modeling procedure, choice of elements, loads and outputs, allow KONE to rank the factors influencing ride comfort, in order of priorities to optimize the user experience, the flow in the building and the elevator product.

6. Acknowledgement

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