Transient Dynamic Computation for Mega-High Rise Lifts

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Abstract. The megatrend of urbanization brings new challenges for the lift industry; the need for keeping the travel time short may conflict with the demand for safety and comfortable ride. In the case of a mega-high building, the performance of the lift system can be substantially affected by the response of the building to various excitation, such as strong winds.

This paper focuses on the prediction of in-car vibrations for a specific lift configuration with various running parameters in the event of building sway, using a chain of multi-physic computation. The core of the computation is a direct transient dynamic finite element method where user subroutines were developed to accommodate installation accuracy in a range of millimetres for a travel in the range of 500 - 1000 m. Aerodynamic loads were considered by using a transient fluid dynamic computation. Behaviour of ropes while the lift is in motion with different building sway parameters and speed profiles were computed using a finite difference method. The computational results were validated in no-sway conditions and the computational method was used for predicting the in-car behaviour during sway conditions.

The advantage of this approach is that the dynamics of the entire structure can be analysed for every lift component: car, sling, roller, roller's stopper; for the entire travel and for different running parameters. This provides the opportunity of optimizing – for example – the lift speed, based on the targeted ride comfort class and lift system performance in various sway conditions.

Finally, to demonstrate the one possible usage of this calculation method, the results of the multi-physic computation were combined with traffic analysis and the probability of various excitations to assess the long-term implication to the lift system performance.

As a result, an enhanced sway operation of the elevator was developed, for which an optimized car speed profile was proposed instead of traditional high wind mode. Although no major improvement of handling capacity on a yearly level could be noticed, the service provided to lift users for highly windy days, will not go unnoticed.

1 INTRODUCTION

The demand for taller buildings creates the challenge of how to ensure outstanding ride comfort of lifts in severe environmental conditions like building sway. To respond to this challenge the lift manufacturers have been forced to use advanced computational solutions for predicting the dynamic behaviour of the car.

In several articles [1, 2, 3, 4], the dynamics of the ropes in sway conditions were studied and analytical models were developed in order to understand their effect on the lift dynamics. However, studies that focused on the effect of building sway to in-car vibrations were very challenging to find.

The focus of this paper is the computation of in-car vibrations, using a chain of multi-physic computation: transient finite element for mechanical and fluid dynamics, differential equations, data from measurements and statistical methods.

In KONE the development and validation of transient computation for in-car vibration started several years ago [5, 6]. After the confidence in the models reached a certain level, their complexity was extended to cover the impact of building sway on in-car vibrations. The computation enables the optimization of the car velocity as a function of sway amplitude, in order to ensure the quality of the lift service in challenging weather conditions. Finally, the impact of using an optimized speed profile for high wind conditions was computed and compared to traditional lift operational methods.

2 SELECTION OF THE COMPUTATIONAL STRATEGY

The computational strategy was chosen based on the frequency range of interest of in-car vibrations, dictated by human perception. Due to human skeleton, ligaments and other damping mechanisms, while standing, ISO8041:2017 recommends a frequency range under 10 Hz for in-plan vibrations and under 80 Hz for vertical vibrations [7]. Multi-body simulation and finite element method were the most suitable methods for this frequency range, however since the flexibility of the building was the focus of the study, finite element was selected.

The next challenge was the size of the model, which included over 500 meters guide rails with misalignments of fractions of millimeters, sling, car, ropes and travelling cables. To overcome this challenge a substructure modelling technique was chosen, where the model was divided into regions (substructures) for which the stiffness, mass and damping matrices were computed independently and reassembled in the global solution. By using a Guyan reduction [8], the mass and stiffness matrix of the substructure are reduced to several retained nodes that significantly decrease the size of the global model. The drawback is that only linear and small displacement behaviour can be modelled accurately with this method. Therefore, the division of the model has to be carefully selected.

The global model of a double deck lift (Fig. 1) consists of guide rails and fishplates modelled as beam elements with variable profile; brackets, modelled as springs; sling and car substructure (Fig. 2) attached to suspension, compensation rope and travelling cable and guide shoes substructure. With this choice, all the components affecting in-car vibrations were considered and evaluated in the computed solution [6].

The air loads due to counterweight passing by (Fig. 3) were computed using finite element method for fluid dynamics and the pressure variation was applied on the walls of the car, for the time of the counterweight transition.

The guide shoes (Fig. 4) were raising also challenges. The levels controlling the wheels, the springs and the stoppers had large displacements and rotation degrees of freedom; therefore, their linearization into one substructure was decreasing the accuracy of solution. The decision was to divide the guide shoes into several regions: substructure without levers (Fig. 5) three substructure for levers (Fig. 6) and model the three stoppers and three springs at global level. The rubber wheels were assumed to be always in contact with the guide rails with a small friction coefficient and to glide along guide rails instead of rotate.

Even with this solution, where separate regions were solved in parallel, the model was too big to be analyzed in reasonable time. For that reason, instead of modelling the misalignments of the guide rails as a geometry in the model, a user element has been defined for each connection between guide rail shoes and guide rail [6]. Within user element subroutine, the misalignments of the guide rails and the displacement of the building due to sway were prescribed. These values were measured for several guide rails and existing buildings and estimated for new projects.

Finally, the rope forces affecting on the sling were computed using a finite difference method and applied as variable load, depending on the car position in the shaft.

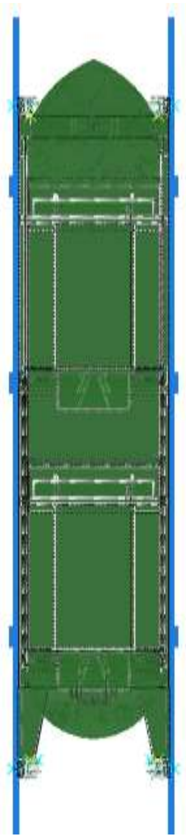

Figure 1 Lift global model

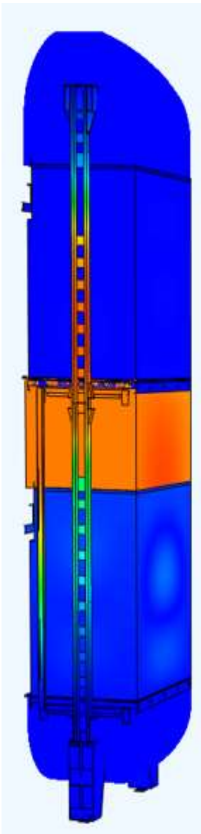

Figure 2 Sling-car substructure

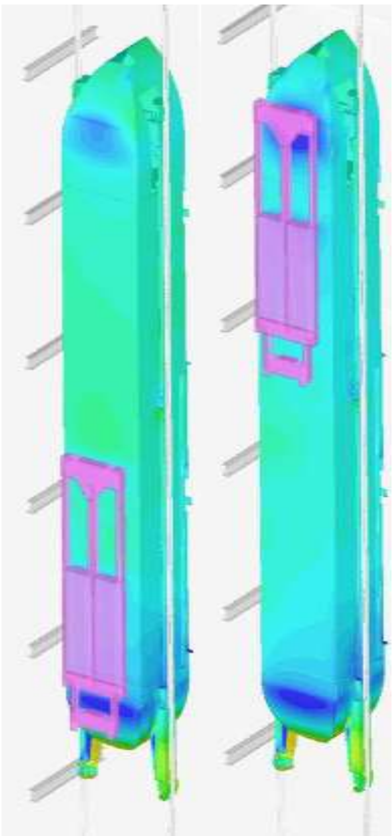

Figure 3 Counterweight impact

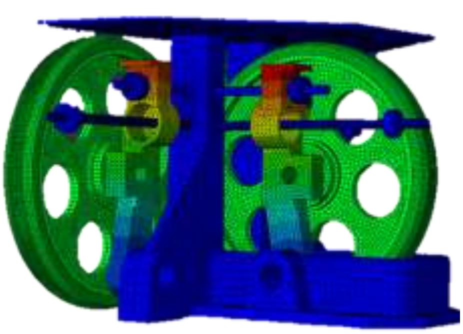

Figure 4 Roller guide shoe

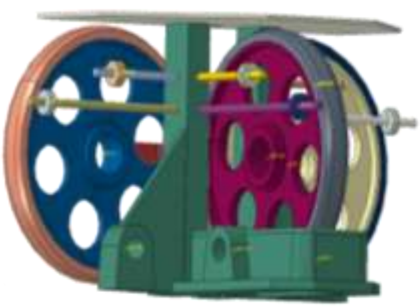

Figure 5 Substructure

Figure 6 Lever

3 LOAD CASES

Several load cases were analysed and compared during this study.

Within the guide shoes substructure, a contact step was applied between wheels and guide rail, followed by an eigenfrequency extraction analysis and the substructure generation.

Within the sling car substructure, a static step containing gravity load, pressure load due to the counterweight passing by was followed by an eigenfrequency extraction and finally the substructure generation.

At global level, the misalignments of the guide rail installation (Fig 7) were applied, using the user element that defines the displacements of the guide shoes rollers. The building sway (Fig. 8) was applied to the brackets fixing the guide rails to the shaft [6].

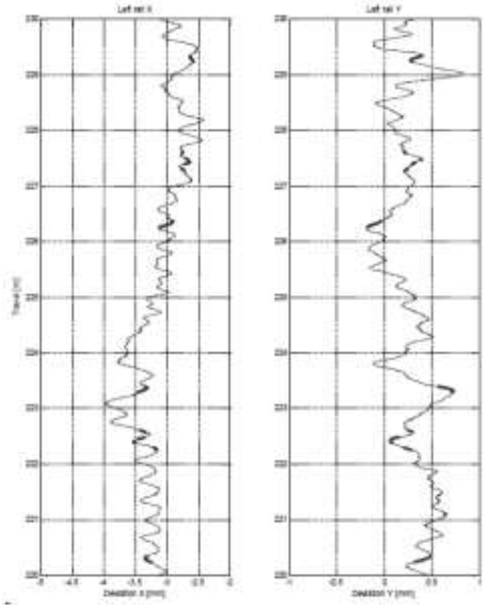

Figure 7 Guide rails misalignments

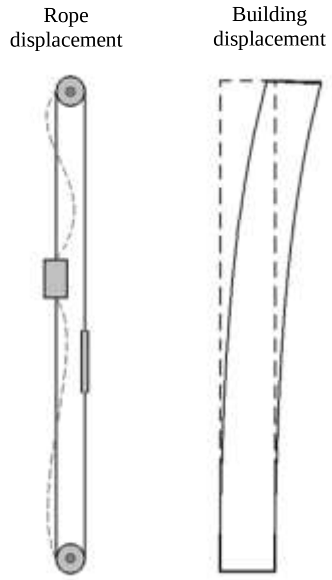

Figure 8 Building sway

The compensating ropes and travelling cable were modeled as user elements where the mass varied with the length of the elements and the suspension and compensating rope forces computed for each velocity profile and sway definition were applied on the sling [6].

The impact of building sway and speed to ride comfort was evaluated using different speed profiles. The in-car vibration had to be analysed as a function of lift speed and building sway and the target was to find the best suitable profile that can ensure a good ride comfort and a minimum travel time.

4 THE EFFECT OF BUILDING SWAY TO LIFT SYSTEM PERFORMANCE

The philosophy of evaluation of the effect of building sway to the lift system performance was adopted from a presentation by Kalliomäki [9]. The specification of the assessed hypothetical lift (group) is given in Table 1. The evaluation was done in three stages: in the first stage the aim was to find a best possible speed profile in sway conditions while maintaining a good level of ride comfort, in the second stage, the effect of these speed profiles on the handling capacity of a lift group was evaluated based on traffic simulations and in the final stage the overall implications of this effect were analysed over a longer period of time by using probability information of different sway magnitudes.

Table 1 Lift parameters

Travel [m]	508	Nominal speed [m/s]	10
Acceleration [m/s^2]	0.8	Start delay [s]	0.7
Jerk [m/s^3]	1.2	Advance door opening distance [m]	0.0
Group size	4	Advance door opening speed [m/s]	0.0
Door opening time [s]	1.5	Passenger transfer time [s]	1.0
Door closing time [s]	3.1	Rated load [passengers]	20
Photocell delay [s]	0.9	Building frequency [Hz]	0.1394

4.1 Speed profile policy selection

In order to evaluate what the impact of building sway and velocity on ride comfort, 19 speed profiles (Fig. 9) for an up-running lift were analyzed for the same sway amplitude of 88mm. Some of the results are presented in Figure 10. For the speed 10m/s speed profile, also the evaluation of sway amplitudes 88mm, 66 mm, 53 mm, 44 mm and no-sway on ride comfort were also done (Fig. 11).

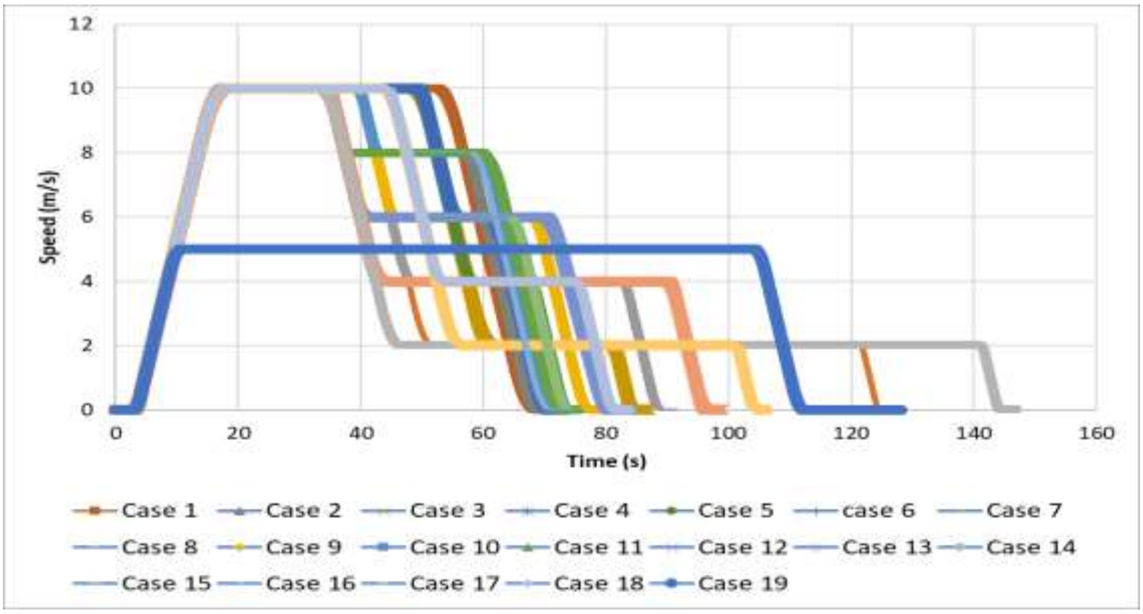

Figure 9 Analyzed speed profiles

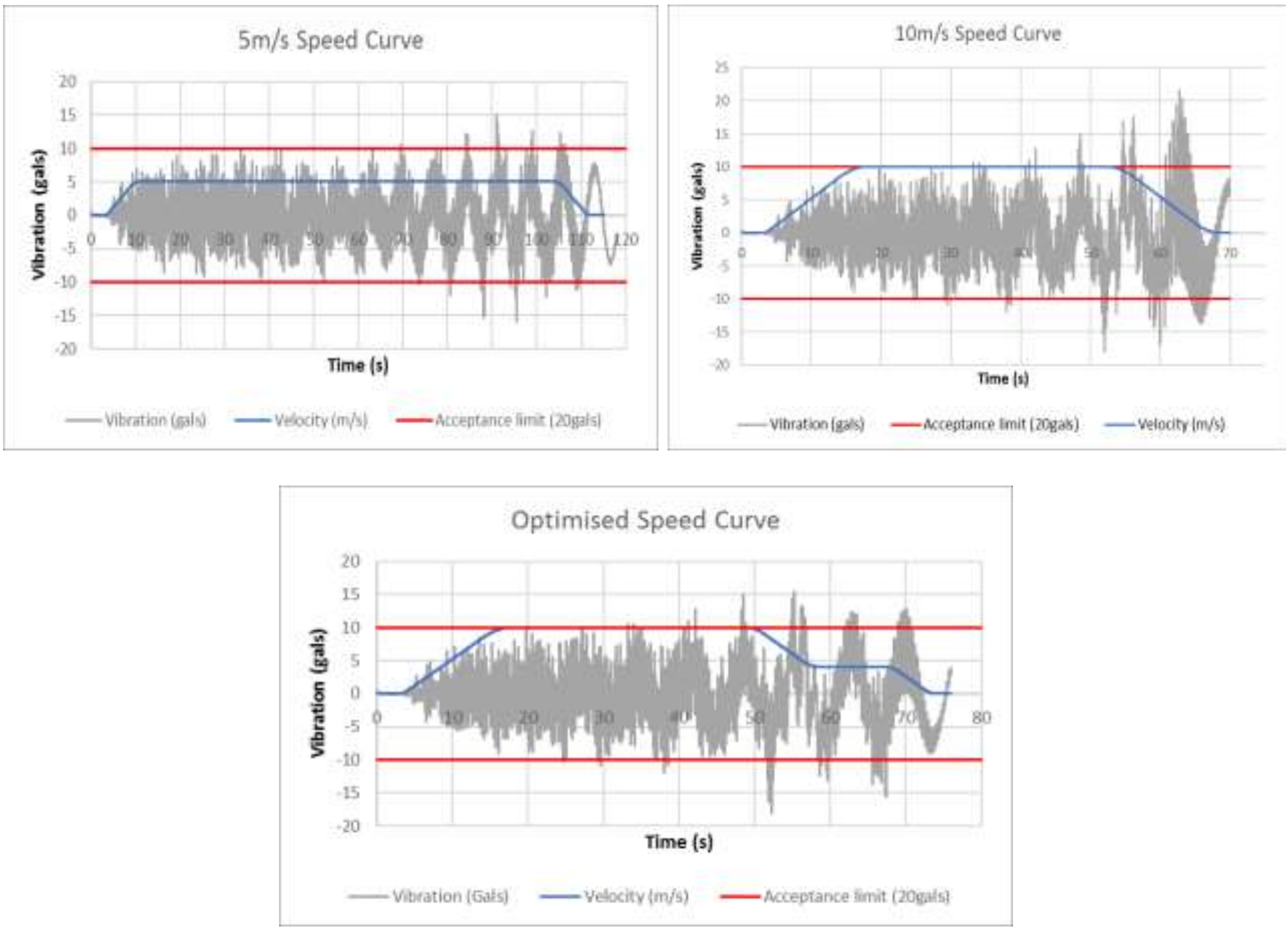

Figure 10 In-car vibrations for different speed profiles

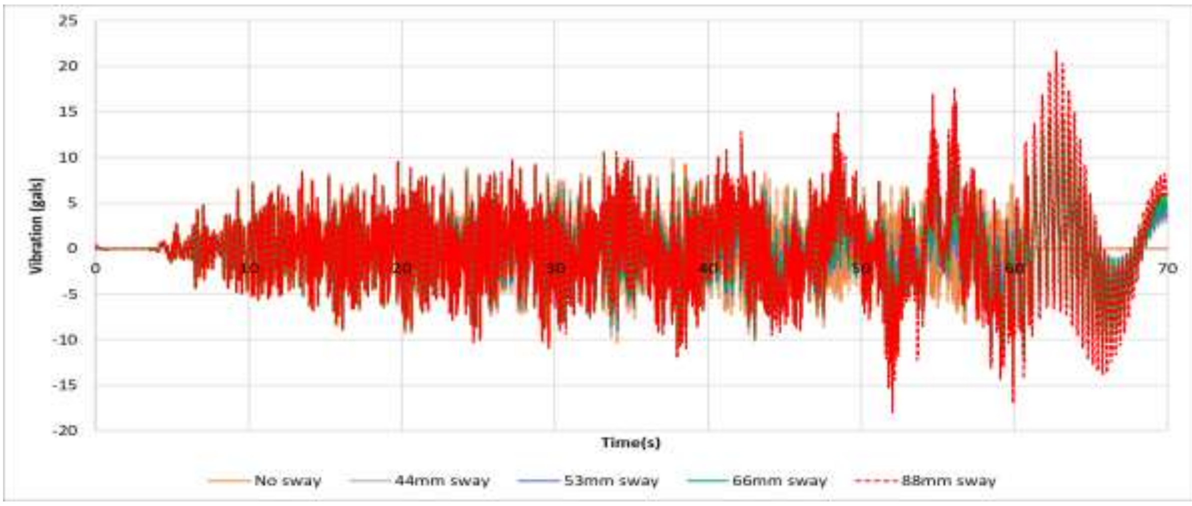

Figure 11 In-car vibration for 10m/s and different building sway amplitudes

For each profile, in-car vibrations were computed and compared against the acceptance criteria, which is – based on KONE ride comfort classes – that the maximum adjacent peak-to-peak magnitude must be under 20 gals.

An analysis of the results indicates (Fig. 11) that only when the car passes the level of 396 m the in-car vibration does not fulfil the acceptance criteria. For the studied case, the optimal solution among considered cases was chosen (Case 16, Fig. 9).

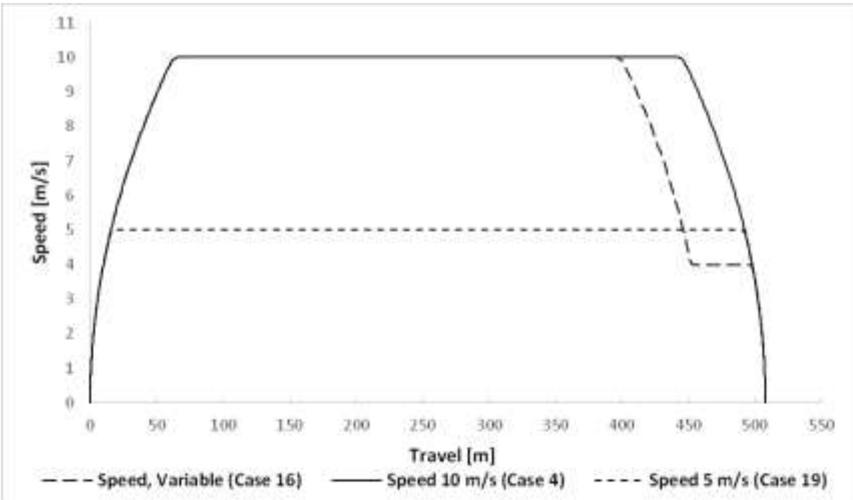

Figure 12 Selected speed profiles

By using 10 m/s profile (Fig. 10), the peak-to-peak car vibration is 28.5 gals, therefore not fulfilling the acceptance criteria. The flight time is 64 s. By using the common solution of reducing the speed to half (5 m/s), the peak-to-peak car vibration is 18.1 gals and the flight time is 109 s. By using the optimised profile (Fig. 12), the car can run with 10 m/s until 396 m and then decelerate to 4 m/s. The peak-to-peak car vibration is 19.7 gals and the flight time is 71s.

Analysing the result (Fig. 11) shows also that ride comfort is always within the acceptable range when the building sway is less than 53 mm. This means that in those conditions the nominal maximum speed of 10 m/s can be used for the whole run, corresponding to less than 20 gals in-car vibrations.

4.2 Effects on handling capacity

This section assesses the impact of different speed strategies applied during a building sway. The impact is measured in terms of handling capacity and waiting time. The former measure is the number of persons the lift group can transport from their origin floors to destinations within a 5-minute period while the latter one is how long passengers need to wait for lifts at lobbies as an average. Two hypothetical lift groups are considered, each consisting of 4 lifts. These lift groups may not satisfy all traffic planning recommendations. Table 1 shows the lift parameter values used in both groups.

In the first group, denoted by Group A, all four lifts are shuttle lifts and they serve only the main entrance level, 0, and the observation deck located at the top of the building at level 508 meters. The second group, Group B, serves the main entrance level and the 20 highest floors. Table 3 gives the building parameters. Population per served floor is assumed to be equal.

For both groups, three different speed profile policies are used. In the first policy, denoted by P10, speed profile for any run is an ideal speed profile with the maximum velocity of 10 m/s (if the maximum velocity is reached), and this policy is used during calm weather. For detailed information about ideal lift kinematics the reader is referred to Peters' study [10]. The second policy, P5, is the same as the first one, except the maximum velocity, which is now restricted to 5 m/s. This policy represents the current practice used during high wind in which the maximum velocity is dropped to half.

In the last policy, PE, speed profile for any floor pair is an ideal speed profile with the maximum velocity of 10 m/s except runs from the main entrance level to upper floors. For those runs the speed profile is formed according to local optimal speed profile for a 508 meter run where the first deceleration to speed 4 m/s starts at level 396 m in order to satisfy acceptance criteria for peak-to-peak vibrations. It should be noted that it takes for a lift about 66 meters to decelerate from 10 m/s to 0 m/s. This means that speed profile for a run from the entrance level to an upper floor that is shorter than 461.8 meters reduces to an ideal speed profile. For convenience, flight times for each speed policy from the entrance level to upper floors are reported in the last three columns in Table 3.

The traffic for both groups are simulated independently of each other using Building Traffic Simulator [11]. Several different traffic patterns are considered, see Table 2.

Table 2 Traffic patterns

Traffic pattern	Traffic components [percent]		
	Incoming	Outgoing	Interfloor
Up-peak	100	0	0
Down-peak	0	100	0
Two-way	50	50	0
Mixed	40	40	20

The simulations results are collected in Table 4. Handling capacity is measured in such a point where the average car load at starts is about 80 % of nominal load. From this one can see that setting the maximum speed to half decreases the handling capacity significantly while using optimized speed profile the handling capacity decreases slightly.

4.3 Long period implications on the service level of the elevator system

In the example the operation of the lift system can be classified in four distinctive modes based on the prevailing weather conditions; normal mode during calm weather, *enhanced sway operation* during moderately high wind, *high wind mode* and *storm mode*. During *storm mode*, the lift operation is ceased and the lift cars are positioned in safe parking areas. During *high wind mode*, the lifts are running at half speed independently of the source and destination floors.

Table 3 Building parameters and flight times from the entrance level, 0, to upper floors

Floor marking	Group A	Group B	Floor Height [m]	Level [m]	Flight time		
					P10	P5	PE
21	S	S	4	508	63.97	108.52	70.89
20	X	S	4	504	63.57	107.72	69.89
19	X	S	4	500	63.17	106.92	68.89
18	X	S	4	496	62.77	106.12	67.89
17	X	S	4	492	62.37	105.32	66.89
16	X	S	4	488	61.97	104.52	65.89
15	X	S	4	484	61.57	103.72	64.89
14	X	S	4	480	61.17	102.92	63.89
13	X	S	4	476	60.77	102.12	62.89
12	X	S	4	472	60.37	101.32	61.89
11	X	S	4	468	59.97	100.52	60.89
10	X	S	4	464	59.57	99.72	59.97
9	X	S	4	460	59.17	98.92	59.17
8	X	S	4	456	58.77	98.12	58.77
7	X	S	4	452	58.37	97.32	58.37
6	X	S	4	448	57.97	96.52	57.97
5	X	S	4	444	57.57	95.72	57.57
4	X	S	4	440	57.17	94.92	57.17
3	X	S	4	436	56.77	94.12	56.77
2	X	S	4	432	56.37	93.32	56.37
1	X	X	428	4	-	-	-
0	S	S	4	0			
S represents served floor while X represents express zone.							

Table 4 Handling capacities and waiting times

Performance measure	Speed policy	Traffic pattern, Group A			Traffic pattern, Group B		
		Up	Down	Two-way	Up	Down	Mixed
Handling capacity [number of passengers / 5min]	P10	107.1	53.9	164	65.2	88	90
	P5	70.7	35	110.6	50.4	62	75.2
	PE	102.9	49.7	143.5	64.4	84	88
Average waiting time [s]	P10	30.0	31.1	65.2	57.0	93.6	87.3
	P5	50.8	56.4	107	72.8	124	105
	PE	31.8	34.8	70.6	61.0	86.2	92.6

During enhanced sway operation, which is the focus of this paper, the variable speed profile is selected only when the car runs from a resonant floor to floors where the rope sway would induce unacceptably high in-car vibrations. This is an advancement over the traditional high wind mode, where, above a certain building sway threshold, all lift operations occur at half speed.

When it comes to designing tall buildings for occupant comfort under wind-induced motion a recent trend has been to evaluate the windstorms with a one-year recurrence interval. This recurrence interval is relevant to occupants' daily lives [12]. This is why a one year observation period was chosen for this study. The target for lift system design is that for normal buildings the *storm mode* is triggered less once per ten years and therefore during this observation period it is assumed the lift operation is never ceased due to sway.

The peak-to-peak acceleration limit of 20 gals set the lowest threshold to peak amplitude of 53 mm at the highest occupied floor. Between amplitudes of 53 and 88 mm the *enhanced sway operation* with variable speed profile may be used and the *storm mode* is activated at the amplitude of 170 mm, which corresponds approximately to a building acceleration of 13 gals. The exceeding of storm threshold is not considered for observation period.

Based on the acceleration characteristics of the case building (Fig. 13) it is expected that during the observation period the amplitude threshold of 53 mm is exceeded on 6 days and the amplitude of 88 mm on 1 day. The duration of these events cannot be gained from the return period data. To get an estimate for the calculation, the yearly wind speed data of the building location was acquired (Fig. 14) and days of high wind speeds where plotted in ½ hour segments (Fig. 15). From this four day sample data, it was estimated that high wind speed periods (> 50 m/s) can last up to 5 hours. For very high wind (> 60 m/s), there is just one measurement point, but taking into consideration the neighbouring high wind segments the duration of very high wind in set to 1 hour. It is noteworthy that the wind on 10.4.2018 is associated with a thunderstorm and due to its short duration it would most likely lack the power to excite the building.

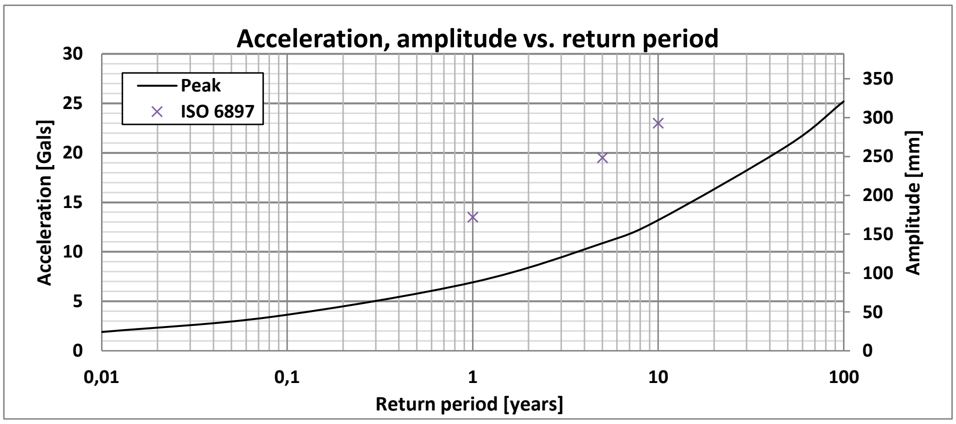

Figure 13 Acceleration and amplitude characteristics of the case study building

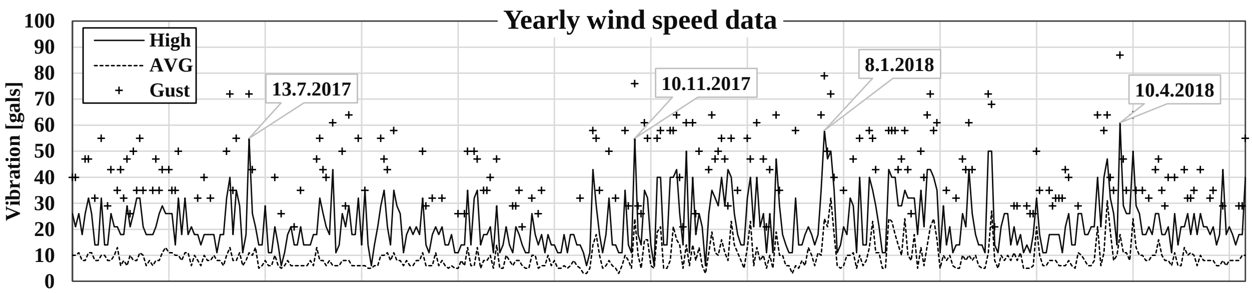

Figure 14 Yearly wind speed data for the location

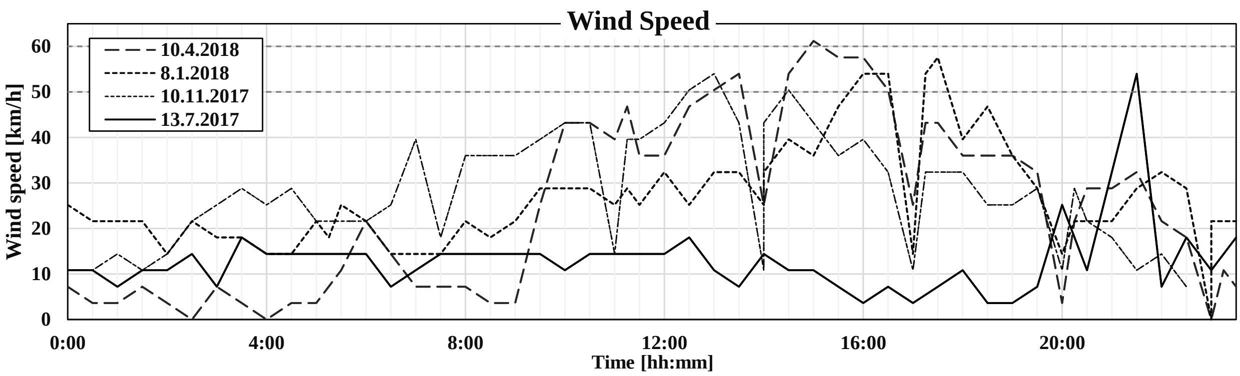

Figure 15 Wind speed data for high wind speed dates

The relative yearly handling capacity is calculated by formula:

$$HC_{relative} = 100\% \times \frac{t_{normal}}{t_{total}} + \frac{HC_{highwind}}{HC_{normal}} \times \frac{t_{highwind}}{t_{total}} + \frac{HC_{ench\_sway}}{HC_{normal}} \times \frac{t_{ench\_sway}}{t_{total}}, \quad (1)$$

where *HC* is handling capacity, *t* is time and t_{total} is total time (1 year). Index *normal* refers to when the lift is operating normally, *high wind* to *high wind mode* and *ench_sway* to *enhanced sway mode.* For simplicity, the two-way or mixed traffic is always assumed for the assessment.

5 RESULTS AND DISCUSSION

In this paper, a multi-physics approach has been used for computing in-car vibrations for different component selections, driving parameters and sway conditions of the building.

By optimization of the speed profile during building sway, a solution can be found for the majority of sway conditions, which fulfils the ride comfort requirement and which increases the lift flight time only moderately. This *enhanced sway operation* allows keeping the handling capacity of the lift system high even on windy days.

For a shuttle lift (Group A) with the *enhanced sway operation*, during the observation period of one year, on 6 days the handling capacity is reduced to 88 % for a period of 5 hours, for 1 day per year the handling capacity is reduced to 67 % for 1 hour and the rest of the time the handling capacity is nominal. The yearly relative handling capacity is 99.953 %. Without the *enhanced sway operation,* on 6 days the handling capacity is reduced to 67 % for a period of 5 hours and on one day per year for one hour. For the rest of the time the handling capacity is nominal. The yearly relative handling capacity is 99.885 %. For Group B, the handling capacity is reduced to 98 % for *enhanced sway operation* and to 84 % for *high wind mode*. The yearly relative handling capacity is 99.991 % with *enhanced sway operation* and 99.942 % without it.

Overall, through this very simplified example, it can be seen that there is no major effect to the handling capacity on yearly level with either approach on either group. However, especially for the shuttle lifts (Group A) without *enhanced sway operation*, it can be expected that during the reduced speed operation a peak in lift traffic will occur which will cause longer waiting periods and longer flight times (see Table 3 and Table 4). This will not go unnoticed by the lift users. By using *enhanced sway operation,* the period on half speed service is considerably reduced and is less likely to occur during peak traffic. Also, the increase in waiting time and flight times during *enhanced sway operation* is less likely to create passenger discomfort.

These results can be assumed to be fairly representative of modern buildings designed with high occupant comfort in mind (offices, hotels, residential buildings). For other structures (TV and observation towers) the outcome might be considerably different.

The Transient Dynamic Computation enables the evaluation of the performance of mega-high rise lifts from a much wider perspective than has been previously possible. This paper presents a multidisciplinary approach by using a practical example where the dynamic computation is combined with ride comfort requirements, traffic-analysis, sway characteristics of the building and climate information. The example demonstrates that through this process it is possible to minimize the negative impacts of building sway to the performance of the lift system. For a practical implementation of this approach there seems to be two possibilities; either to assess the performance in sway conditions separately for individual runs and apply traffic modes precisely based on actual traffic forecast for high accuracy or establish a generic database of predefined cases for quick fit-for-purpose speed policy selection.

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BIOGRAPHICAL DETAILS

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