EXPERIMENTAL VALIDATION OF AN ESCALATOR SIMULATION MODEL

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***Abstract*––** **Today's escalator mechanical systems are based on 100-year-old conventional designs. A sustainable innovation is possible but the industrial inertia of making a prototype for each design has to be changed. This document describes a methodological approach for comparing and validating simulation models through measurements performed on a prototype of a recently patented design. The methodology is based in the adjustment of parameters and the synchronization of cyclic signals in time, allowing the comparison of measurements and simulated outputs. Results shows a high level of correlation between the signals in the time and frequency domains, thus validating the dynamic model and the methodology here presented.**

***Keywords*––** **Escalator; validation; dynamic; multibody; vertical transport.**

I. INTRODUCTION

Vertical transport needs new ways to study and develop new concepts. At present, innovative design tasks have to be sustainable since any idea needs to be physically manufactured in order to be tested. This implies a high economic and time cost, compared with simulation models. Therefore, the production of ideas must be automated and the test time of each idea has to be reduced using simulation models.

There are a lot of creative techniques, such as brainstorming sessions or the TRIZ technique, which allows improving the first stages of new designs and are useful in solving contradictions that may appear at any point in the product cycle.

These ideas or improvements of new or existing designs have to be tested in a reliable way and in a short time. The best way to reach this goal is to avoid real prototype construction and to develop dynamic simulation models which represent and characterize the main behavior of the system.

Some methodologies (Gul and Guneri, 2012; Cho and Kim, 2013) have already been developed for solving, analyzing and developing new or existing designs by using creativity tools and techniques and advanced simulation models. Escalator design is more than a century old but the way of working presented here provides another point of view and new concepts in vertical transport.

In the analyzed literature, there is only one dynamic simulation model validated (Kwon, 1998). This model represents a conventional escalator.

This paper describes a methodology used to validate a dynamic model of a particular escalator with an innovative design. Several dynamic models (Cabanellas Becerra *et al*., 2008a) have been developed by means of common methodologies. Therefore, the model validation aims to validate pre-processing, modelling and post-processing stages.

Although there are other dynamic simulation programs available on the market that can simulate the dynamic behaviour of a multibody system, such as ADAMS (Orlandea *et al.*, 1977), DADS (Haug, 1985), RECURDYN (Liu, 2008; functionbay, 2017), etc.; it was decided to choose Simpack (Klisch, 1999; simpack, 2017) as it meets all the minimum requirements. Simpack is widely experienced in multibody systems modelled with this program. It has an advanced module for creating chain drive systems, which is a common feature of escalators and moving walkways. Figure 1 shows a model developed with the Simpack CHAIN module.

In addition, this software allows access to the model implementation code so that the degree of automation for creating elements, joints, constraints and repeated force elements can be increased. This automation of the work to create a code that can be read by Simpack was performed by using MATLAB programs. Simpack also allows the implementation of advanced control systems using SIMULINK, and both programs are able to communicate with each other at every integration step of a simulation by using what are called co-simulations. This type of control system is a potential advantage that has not been used in the development of the model presented in this paper and which will be the subject of future lines of research.

The validation methodology herein described includes some developments that are directly applicable to any validation process of multibody systems.

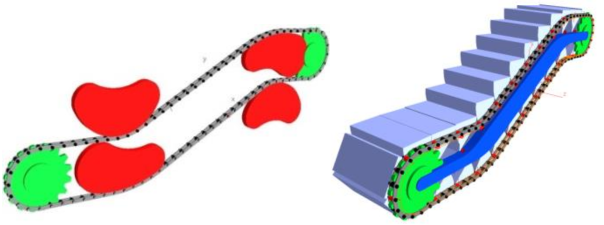

Figure 1. Escalator model developed with the Simpack CHAIN module.

II. MODEL DESCRIPTION

The design of the escalator intended for validation represents a new concept in the world of vertical elevation due to its innovative nature (Muñiz Camblor *et al.*, 2010). This design includes safety elements that are not yet available on a commercial level, such as the moving skirt, which eliminates any entrapments and shearing due to the clearance and relative velocity between the steps and their current fixed skirt.

As can be seen from the patent (Muñiz Camblor *et al.*, 2010), from which the images in Figure 2 are taken, the working system is such that the step tread and risers form part of different bodies, articulating with one another. The moving skirt forms a body with the steps, all solidly joined to the long chain link, thereby optimizing the space in the turnarounds. The assembled system is illustrated in Figure 3.

This escalator has another difference compared to the conventional model, a drive system that consists of a gear wheel located at the upper turnaround that engages the roller chains that move the steps.

The model to be validated has a linear drive system located in the straight zone of the upper inclined zone, as Figure **4** illustrates the different parts that compose an escalator. The advantage of a linear drive appears with the use

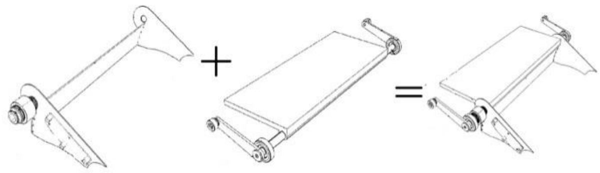

Figure 2. Drive system and moving skirt.

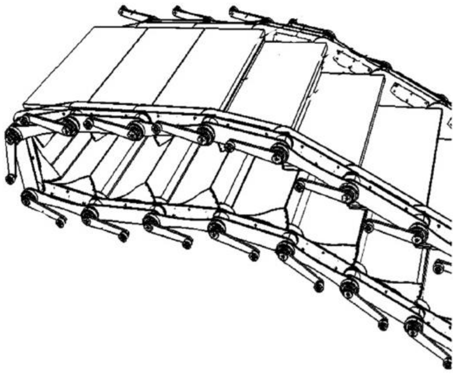

Figure 3. Escalator system to be validated.

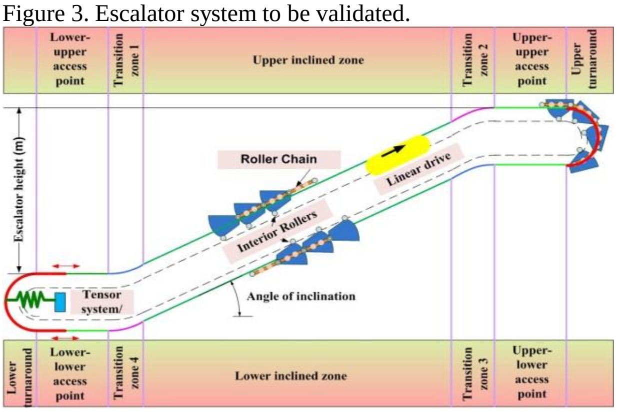

Figure 4. Innovative escalator with linear drive.

of guides in the curved zones designed to eliminate the chain effect which causes a polygonization of the velocity. This effect is formulated below and is based on the notation in Fig. 5.

If $w = \frac{d\alpha}{dt}$ is a constant angular velocity and L is the chain link pitch, then

$$\begin{cases} X_1 = -R\cdot\cos(\alpha) \\ Y_1 = R\cdot\sin(\alpha) \end{cases}$$

$$\begin{cases} X_{2'} = X_{1'} + \sqrt{L^2 - (Y_{2'} - Y_{1'})^2} \\ Y_{2'} = R \end{cases} \quad (1)$$

$$V_{2'} = \frac{dX_{2'}}{dt}$$

$$V_{2'} = w\cdot\left[R\cdot\sin(\alpha) + \frac{R\cdot\cos(\alpha)}{\sqrt{\left(\frac{L}{R(1-\sin(\alpha))}\right)^2 - 1}}\right] \quad (2)$$

with

$$\alpha \,\epsilon \left(\frac{\pi}{2} - 2asin\left(\frac{L}{2R}\right), \frac{\pi}{2}\right)$$

Therefore, the linear velocity of a roller is represented as V_2 in the equation and in Fig. 6, where V_2 variation can be appreciated for a conventional traction system with constant angular speed at turning zone. Linear velocity considered in this case was 0.5 m/s.

III. DYNAMIC MODEL

Both the dynamic model to be validated as well as the prototype has been made full-scale. All the mass and inertial characteristics of each body were introduced into Simpack by taking CAD models, such data being stiffnesses and roller-guide contacts.

Figure 7 shows the dynamic simulation model implemented in Simpack. It can be observed that as with the real prototype it does not include the risers and moving skirts for the dynamic analysis of the system.

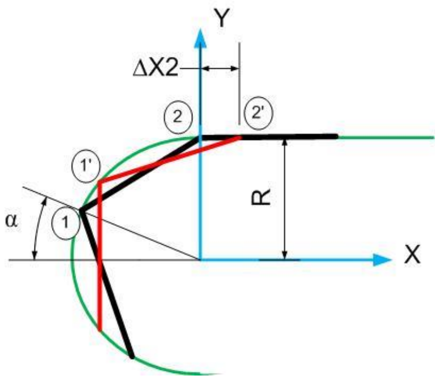

Figure 5. Polygonization effect study in a turnaround curve.

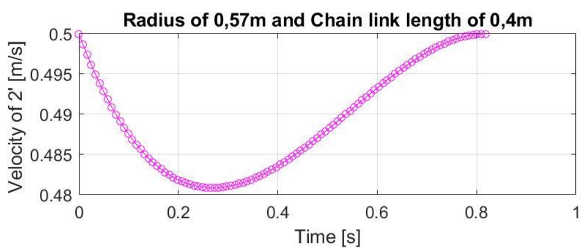

Figure 6. Velocity of a roller going out to the right part of the guide.

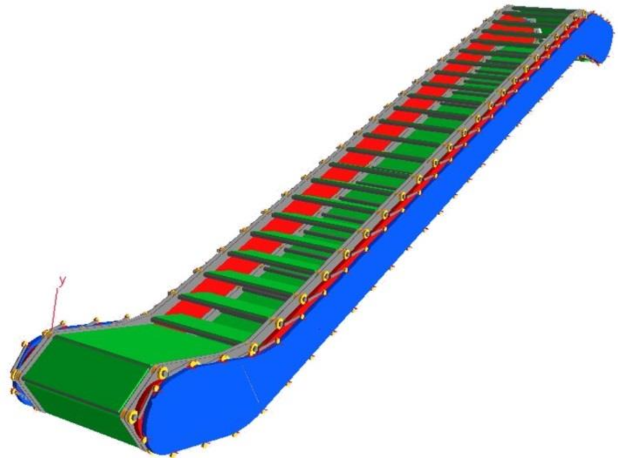

Figure 7. Full dynamic simulation model of an escalator new design.

Table 1. Roller chain main parameters

Parameters	Values
Number of Links and Rollers	60
Chain Link Pitch (m)	0.405
Guide-Roller Contact Stiffness (N/m)	3.5E6
Linear Velocity (m/s)	0.5
Escalator Height (m)	4.5
Inclination Angle (º)	30
Roller Diameter (m)	0.075
Tensioner stiffness (N/m)	3E4
Pre-Load of full Tensioner Station (N)	3E3-6E3

The methodology for implementing the dynamic roller chain model has been described in detail in other publications (Cano-Moreno *et al.*, 2009) where it has been applied to previous models. However, for this model, the basic known parameters referring to the roller chains can be summarised in Table 1.

IV. VALIDATION METHODOLOGY

The validation methodology presented in this paper includes all processes related with two main systems: instrumented prototype and simulated model. Figure 8 shows how the validation methodology works. The flowchart shows how real measurement signals have been used in order to adjust some parameters, emphasizing the linear velocity of the escalator. Once the unknown parameters were properly adjusted, as it will be described herein, the experiment design is simulated again. The next step consists of comparing measured and simulated signals, where signal synchronization methodology will take place. Signals synchronization methodology use cyclic property of signals to superimpose real and simulated signal in the time domain. This kind of synchronization allows comparisons point to point.

A. Experiment design

In order to properly validate the simulation model several cases were defined to compare experimental and simulated results. The following list shows the four parameters that were studied during the experiment:

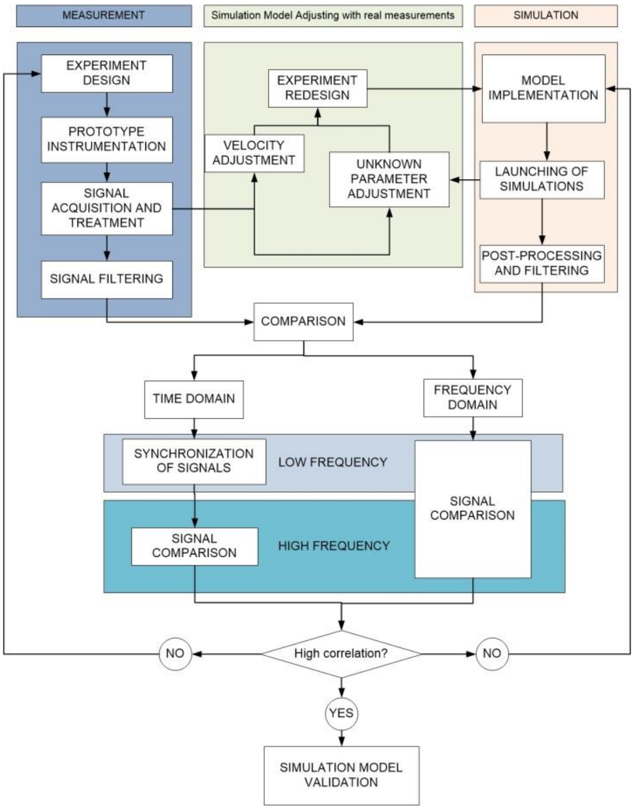

Figure 8. Validation Methodology scheme.

- Linear Velocity of roller chain: low velocity and high velocity
- Direction of engine rotation: upstairs and downstairs
- Load: empty and fully loaded escalator
- Tensor preload: low preload and high preload.

There are four parameters and two levels per parameter. Therefore, 16 cases have been measured, adjusted, simulated and compared.

B. Prototype Instrumentation and loading

The main variables of an escalator were previously identified, see Table 1. These variables characterize the overall dynamic behaviour of most escalators, but a check will need to be made between the measured and simulated model to adjust unknown parameters and to validate the simulating model. The signals for validation are:

- The longitudinal force of a chain link of the roller chain.
- Roller-guide contact force of the rollers that belong to the roller chain.
- Tensioner displacement.
- Step accelerations.

The first and second outputs are closely related due to the geometry of the guide. So, the validation of one of them involves the other. In this case, longitudinal force was calculated from gauges (Micro-Measurements model CEA-06-250UW-350) located on the chain links, as shown in Figure 9. A total number of 16 gauges were located on four chain links, two per side. These locations allow studying load distribution and identifying asymmetries.

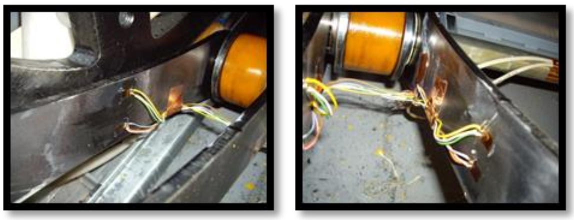

Figure 9. Gauge location on measured prototype.

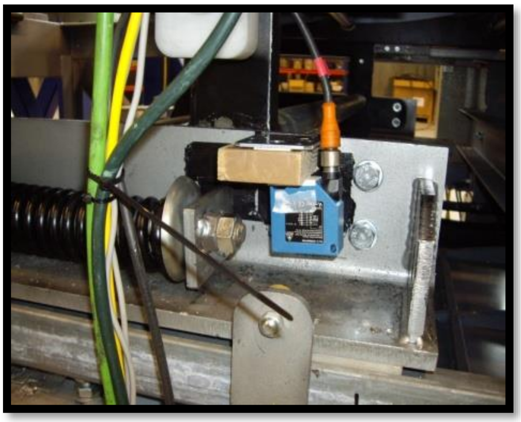

Figure 10. Reflex sensor for measuring tensioner displacement.

Figure 11. Instrumented steps of the measured prototype.

The displacement of the tensioner was measured by using a reflex sensor, showed in Fig. 10.

Three accelerometers were located on the same step. Each accelerometer was oriented along each of the three directions of the space. As Fig. 11 shows, all data registers, signal conditioners and batteries were fixed below two adjacent steps avoiding any interference with the rest of the bodies while the escalator was working.

A counterweight system was used for simulating the loaded cases in the test rig. This mechanism was designed specifically for this prototype. However, it will be used in other tests and designs. This system can be used to test some cases:

- Different weights per step, including some empty steps.
- Asymmetric or symmetric load.
- Variable load, changing the weight in each step should it be required.

In addition, this design can be used at the same velocity range as for escalators. Therefore, this instrumented prototype is able to simulate all defined loaded cases by synchronizing some parameters between the escalator and the load system.

C. Velocity Adjustment

Although in the experiments the velocity of the escalator was adjusted at a previous defined velocity, real velocity was somewhat different. The exact value of this velocity was calculated from the main frequency of the displacement of the tensioner, measured with a laser sensor. This frequency is associated with the length of the chain links of the roller chain.

$$f_{Theoretical} = \frac{1}{T_{Theoretical}} = \frac{V_{Theoretical}}{L_{Theoretical}} \quad (3)$$

$$V_{Real} = f_{Real} \cdot L_{Real} \; . \quad (4)$$

Lengths of chain links are deemed to be constant due to the fact that there are very small deformations. Then, the real velocity was calculated as Eq. 3 and Eq. 4 show. Differences between theoretical and real velocity are lower than 7 % for all cases. Here we define the theoretical velocity as the setup velocity, and the measured velocity as the real. Therefore, these corrections are essential since some comparisons will be in the frequency domain.

A velocity adjustment allows redesigning the experiment and simulating the model more closely to the experimental conditions.

V. RESULTS AND DISCUSSION

After signals treatment, parameters adjustment and signals synchronization, the simulated model can be compared with measurements. In general, lowpass filters (order 4) type Butterworth have been applied for the comparison between measured and simulated signals. Unless indicated, the cutoff frequency is 2 Hz.

A. Longitudinal chain link force

The correlation coefficients for this variable have a mean value of more than 85%. In the frequency domain, the correlation between signals is increased to reach values of more than 99% correlation coefficient (Fig. 12).

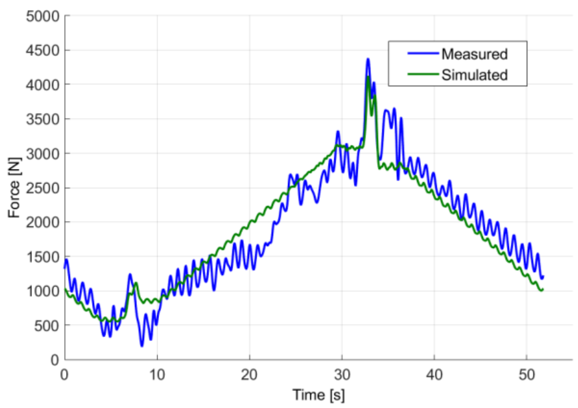

Figure 12. Longitudinal chain link force.

B. Acceleration of the escalator step

The correlation coefficient between these signals reaches a mean value of 60 % up to 2 Hz of cutoff frequency and 80 up to 0.2 Hz. On the other hand, correlation coefficients between signals in the frequency domain reach values of more than 90 % (Fig. 13).

C. Tensioner Station Displacement

The amplitude values correlate highly between the experimental and simulated models. The correlation coefficient in the time domain has a mean value of 75 % for an escalator cycle (Fig. 14).

In the frequency domain, the correlation between all compared signals is increased by 8% as a mean value. As an example, in Figure **15**, the tensioner main frequency is 1.16 Hz, so, taking into account that chain link length is 0.405 m., we can calculate the adjusted velocity following Eq. 4. Therefore, the adjusted velocity would be V=1.16*0,405=0.47 m/s, meanwhile setup velocity was 0.5m/s.

VI. CONCLUSIONS

There are several validation levels, from qualitative to quantitative comparisons (Sargent, 2005; Barlas, 1994; Kleijnen, 1995).

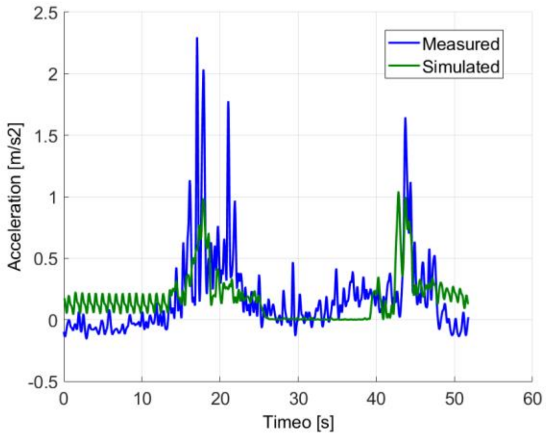

Figure 13. Acceleration of the escalator step.

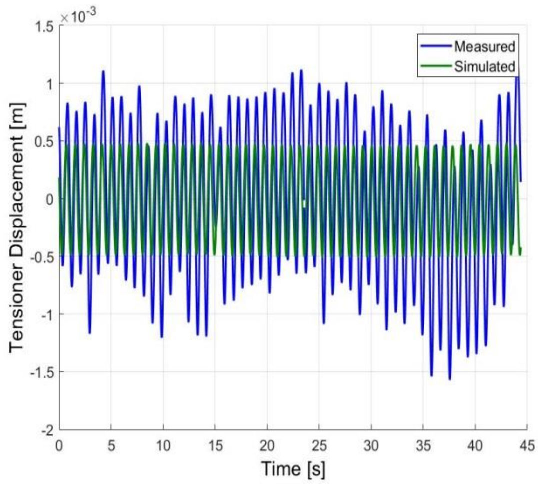

Figure 14. Tensioner Station Displacement (time domain).

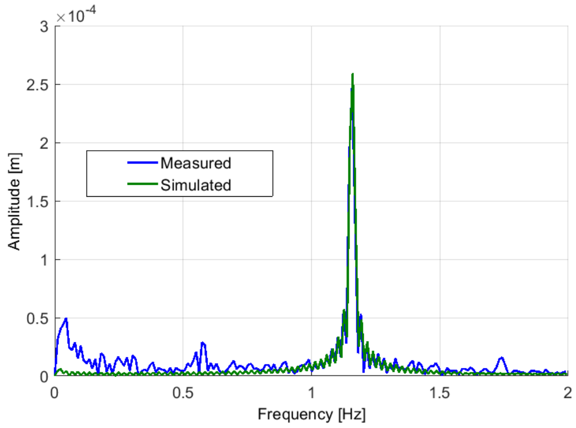

Figure 15. Tensioner Station Displacement (frequency domain).

The methodology described in this paper allows signal synchronization for quantitative and qualitative comparison of measured and simulated signals. In addition, velocity adjustment from setup to calculated velocity from measurements, thanks to tensioner main frequency identification, supposes an innovative method for knowing the real velocity of a closed roller chain.

Qualitative comparison can also be achieved since compared signals are very similar as it is shown in Figures 12, 13, 14 and 15. For quantitative comparison between signals correlation coefficient has been calculated. High values of these correlations validate the simulated dynamic model, as well as all the developed methodologies and tools for implementing simulation models.

Simulation model validation involves the validation of the methodology of implementing simulating models. Therefore, it means than more real prototypes are unnecessary for most of new developed escalator layouts: roller guide geometries, inertia and material properties, length of chain links, parameter variation, traction system position, different velocities and load states. So, improvement of the research in the existing designs will be faster and more economical. In addition, modelling methodology can be used for similar models.

These developments catalyze innovation process of vertical transport field that have been desmonstrated to be stagnated (Cano-Moreno and Cabanellas Becerra, 2017; Cabanellas Becerra *et al.*, 2008b).

As an advancement of the state of the art, the most complete validation published up to now of a dynamic model of escalator is presented. This validation implies that the methodology for generating these models is correct and will allow testing new ideas or optimizing existing ones, without losing the time and cost involved in making prototypes in real size. This will be the way forward for the vertical transport sector to be competitive in the innovation process, both in reducing time and costs.

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Received: January 16, 2018.
Sent to Subject Editor: February 1, 2018.
Accepted: April 30, 2019.
Recommended by Subject Editor: Esteban Anoardo.