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Parametric virtual concept design of heavy machinery: a case study application

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Abstract: Virtual prototyping enables the validation and optimization of machinery equivalent to physical testing, saving time and costs in the product development, especially in case of heavy machines with complex motions. However, virtual prototyping is usually deployed only at the end of the design process, when product architecture is already developed. The present paper discusses the introduction of virtual prototypes since conceptual design stage as Virtual Concepts in which coarse models of machinery design variants are simulated obtaining useful information, sometimes fundamental to support best design choices. Virtual Concept modeling and preliminary validation and its later integration to a Virtual Prototype are expressly investigated using Multi Body Dynamics software. A verification case study on a large vibrating screen demonstrates that dynamic Virtual Concepts enable easier and effective evaluations on the design variants and increase the design process predictability.

Key words: Virtual Prototype, Virtual Concept, design process, CAD based simulation, vibrating screen.

1- Introduction

A design process must develop technically successful and profitable products, identifying since early stages the best product architecture. The design solutions must be defined, that is forecasting the actual performances before manufacturing any single part. Then, sooner or later, the parameters tuning and the performances verification require one or more prototypes.

Important research efforts are focused to develop methods and technologies for setting up Virtual Prototypes (VPs), to identify and solve design flaws before physical testing. First a 3D CAD model is generated, enabling then to simulate the prototype behaviors with Computer Aided Engineering (CAE) software, **[AL1]**. As for mechanical engineering, Multi Body Dynamics (MBD) enables very effective evaluations of the machine evolutions in time. Since VPs must enable testing and data gathering similarly to physical prototypes, a deeper modeling of the machine behaviors requires the integration of different modeling techniques and simulation tools. Multiphysics combines the VP with other numerical models, as e.g. heat transport and thermal stresses, electromechanical or fluid structure interaction, chemical reactions, and process physics, **[AG]**, **[BS]**, **[D]**. Finally, different simulation models can be synchronized to run in parallel including also the control system, **[AL2]**, **[PB2]**.

Literature reports many applications where virtual prototyping enables a very deep analysis of the design performances, **[HL]**, **[GR]**, however the main drawback is still the modeling long time effort. Besides, modeling can start only after the machine layout is defined, especially in case the accurate CAD models are required, severely delaying the investigation on different design alternatives, which is assumed as based on the designer experience in the conceptual design stage and barely aided by numerical models. This method can be quite questionable since conceptual design has a decisive influence on the overall system. Many behaviors result from multiple interactions between the machine elements, difficult or impossible to evaluate by simple formulas, and better and maybe more economic but unconventional solutions are limited by the conventions stored in the design office. Possible design contradictions would be noticed much later during development, when adjustments are difficult to handle. So an engineering method to link design specifications and solutions in the early development stages would drastically improve the overall efficiency of the development process, **[RB]**.

Since virtual prototyping and simulations allow saving times and costs by early errors identification on a digital model of the future product, we propose the integrated adoption of VPs as Virtual Concepts (VCs) in the conceptual design stage, to identify the best product architecture. Assuming a Top-Down design methodology, **[PB1]**, the feasibility of many different design alternatives is quickly evaluated on VCs, before key decisions are made. Since many working principles of heavy machinery are achieved through mechanisms with complex motions, in the present work the VCs are set up as MBD models. The other problems, such as fluid dynamics, heat transfer and interaction with electric motors actuation, are considered important but side

phenomena, thus studied in depth in the next embodiment phase which follows the conceptual one. However, the VCs methodology will be still valid even if it can be extended for specific application with other physics models. The VCs are here coarse models fast set up with just the necessary basic features. Very important is the integration of MBD modeling within the CAD software, to evaluate dynamic geometries and not just mockups, to reuse the parameters automatically created with the CAD models and to keep a system perspective accounting for trajectories, envelopes and collisions. The evaluations extensively look for innovations and reject the unsuitable concepts. Furthermore, the main design parameters are automatically tuned, reducing the risk of not recognizing bad design flaws.
The paper is organized as follows: Section 2 argues the main parameters collection for the VCs set up, then the reuse and refinement of the models from the selected VC to prototype is described in Section 3, a case study on a vibrating screen for inert materials is reported and discussed in Section 4, followed by the conclusions of the paper.

2- Virtual Concept modeling

The Top-Down design approach breaks down the design specifications into essential problems through abstraction. The problems must then be solved by working principles, combined into a working structure. The synthesis of the working principles behaviors delivers the system performances. Since the effects of the behaviors integration cannot be trivially assessed, each integration structure is roughly analyzed by a VC. In order to time effectively assess the different design variants, the modeling must be simplified, including all but only the basic features necessary for its quick set up, and possibly exploiting the tools yet available into the design office. The use of a CAD software can then be advanced in the conceptual design stage to reuse its modeling capabilities for part geometry and assembly kinematics, while a MBD add-in is the necessary extension for evaluating dynamics. Preliminary virtual experiments assess then the advantages and limitations of the concept variants, passing to the sequent virtual prototyping the best candidate(s) only.

Mating interfaces: in [W1] the motions in an assembly are limited by mates and contacts. A mate surface generates a condition of geometric compatibility, eliminating one or more Degrees-Of-Freedom (DOF). Contact surfaces are more hyperstatic connections with stresses and strains which make stable a positioning. VC foundation should rely on mates, which determine the degrees of freedom of the assembly, thus the allowed motions, delivering the key characteristics. On the contrary, the contacts mean static indeterminacy, too complex to model at VC stage. A schematic modeling of the mates is sufficient to numerically fast define how the parts kinematically interact together.

3D dynamic parameters: 3D CAD software automatically computes the mass properties of a part or assembly, as volume, mass, center of gravity, principal axes of inertia and inertia matrices, which are difficult to calculate otherwise. A MBD tool embedded in a CAD software then natively reuses such parameters, that, even if coarse, are useful to identify the strengths and weaknesses of the design solution. First attempt primitive geometries are very often sufficient to represent the dynamic parameters. The material density information is essential for the VC, since it determines some design main parameters, and the material class must be here advanced. The exact chemical composition can wait for sequent design stages.

Working principle(s): a VC should describe the basic working principle. Gravity, functional contacts and lumped features, as actuators, ideal springs, forces and dampers may complete the model. Of course only simplified parameters are necessary and sufficient to represent a behavior. The top problem should be broken down to individual elements to be separately analyzed. In this stage, already known design solutions can be grouped in big chunks and modeled as black boxes, just to pass variables to the other elements. Other phenomena can be introduced as logical or numerical functions, or as splines interpolating external data stored in lookup tables.

Subsystem critical resource budget: the different working principles, synthesized to deliver the system performances, may have to share one or more critical resources with limited availability in the system. It can be the case of mass, stiffness, allowable error or other important side effects and costs-determining parameters. Following the same Top-Down design approach, the goal is to simplify the main design problem by allocating the system resources onto the subsystems. Specific information must complement the model, thus creating rules on the aforementioned 3D CAD parameters or including annotations or even external documents into the CAD feature tree. Not only the parameters values are important but also their distribution, because they are nonlinearly combined into the overall model. The critical resource budget is to be updated during the conceptual design stage and the budget shares have to be satisfied by the subsystems, but the sharing can be reconsidered in case of criticalities. That way, the design more safely achieves the overall performances while, at the same time, saves time and cost for not trying to uselessly save resource usage.

Simplified CAD envelope: a CAD envelope identifies collisions and arranges the subsystems in layout. The allowable envelope for a subsystem can be viewed as another subsystem critical resource share. However, it is separately discussed because it is an important resource and always necessary and it is an obvious visualization of the VC into a CAD based tool.

3- From Virtual Concept to Virtual Prototype

The VP of a machine should reuse the VCs features. The subsystems comply with the main parameters from the previous conceptual design stage even during embodiment and detail design stages. The given critical resource share and the allowable CAD envelope are restrictions for the design and must never be exceeded. Just little refinements are allowed and the conceptual stage can be gone over again with bigger modifications only if an important review

demand arises.
The VP include then the necessary features for a deeper evaluation, as contacts, detailed CAD geometries, more refined working principles, now also with secondary effects and errors models.

Mates and contacts: the mates are now designed as durable and practically manufacturable ones for strength and geometric compatibility. The assembly process must be advanced and eventually reviewed to result in subsystems with robust behaviors. Mates are then fixed by the contacts. Exact contact forces and deformation have also to be included in the model.

Detailed CAD model: the CAD model is now refined with detailed geometries, toward the definitive ones for the definition of the technical drawings. The conceptual design stage followed a Top-Down method but virtual prototyping must now receive Bottom-Up solutions to the problems also. In fact economic feasibility requires reusing commercial or existing solutions. These solutions usually allow only minor modifications and their CAD models are already available, so they act as new constraints for the custom solutions.

Finely dimensioned working principle(s): the working principle must now include the parameters as detailed as possible, compatibly with the time schedule and with the necessary accuracy of the virtual model with the physical. The lumped parameters can be distributed, and the rigid bodies are integrated with compliances and stiffness. Other than the main effects, also the secondary are here included in the model.

Errors models: errors are a special class of behavioral models which address particular scenarios. In fact position actuators can introduce errors to account for non-nominal scenarios and transitions between them. It is the case of thermal effects or other operation induced deformations.

4- Case study on a vibrating screen for inert materials

This section reports about the setting up of the VCs and the sequent virtual prototyping of a heavy machine which undergoes to very rough working conditions. A vibrating screen is a mechanical sieve used in the selection of quarry and mining inert materials and crushed aggregates by their mean dimensions. The virtual models were defined within SolidWorks CAD and the integrated Motion tools.

4.1 – Virtual Concepts for the vibrating screen

The analysis on the existing solutions reveals that the screen has to vibrate along two directions. The vertical movements separate the materials from the screen, loosing contact and enabling front discharge or downfall. The horizontal movements in the flow direction are necessary to advance and discharge the materials. The third direction is to be avoided for simplicity sake, other than for it is useless. Two different working structures are then evaluated as best candidates. They adopt similar working principles, as shown in Fig.1a and Fig.1b. The whole screen structure is moved by synchronous centrifugal forces originated from the eccentric

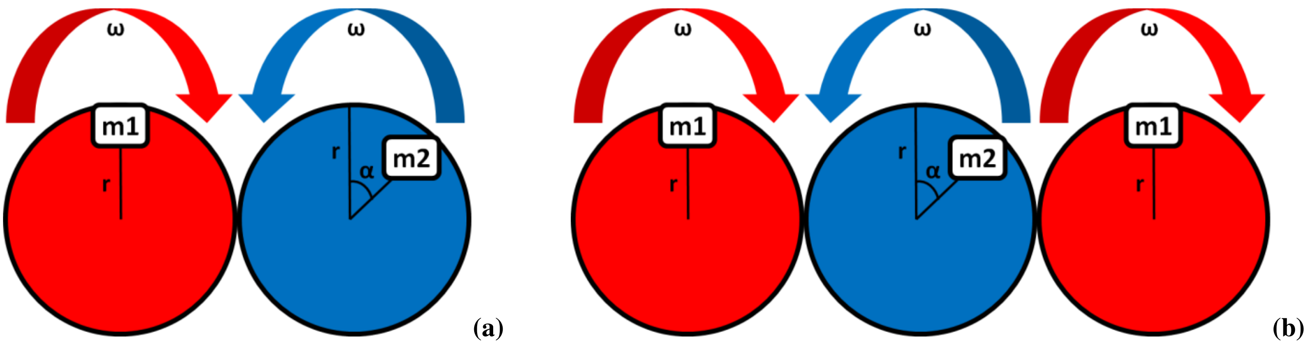

Figure 1: Schematic of two working principles with two (a) or three (b) counter-rotating flywheels.

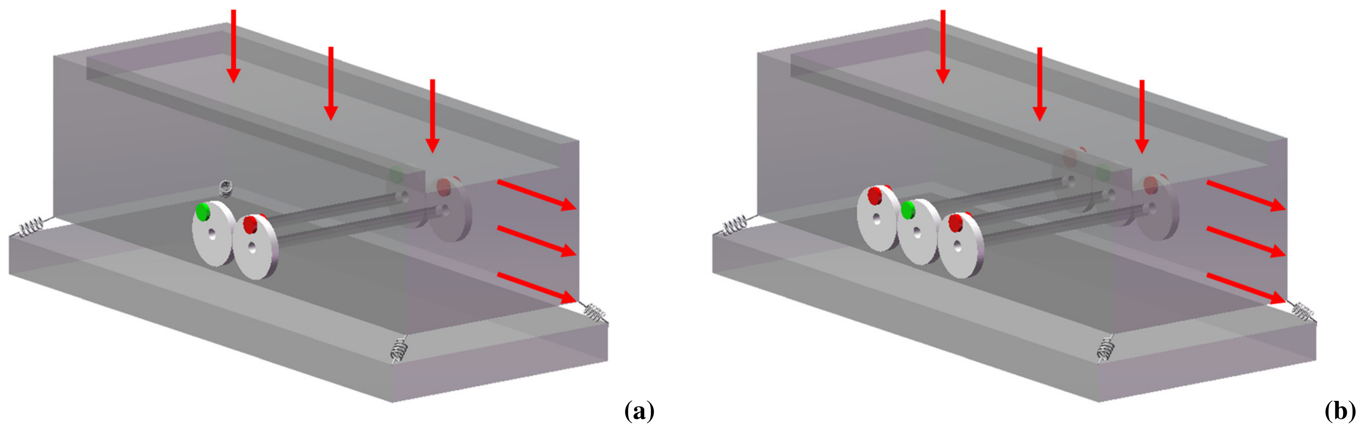

Figure 2: VCs of the two working structures with the principles with two (a) or three (b) counter-rotating flywheels.

masses of two or three counter-rotating flywheels. The basic parameters are the eccentric masses m1 and m2, the radius r, the angular velocity ω and the phase angle α, but the ways how they combine each other and with the other working principles in the working structures in the two cases are not easy to evaluate. Then, Fig.2a and Fig.2b show the respective VCs. The arrows just clarify the material charging and discharging directions. Screen dimensions and suspension springs are other working principles, interacting with the vibration sources principles.

The simulations of the VCs reveal that in both cases the magnitude of the vertical (z) and horizontal (x) displacements can be adjusted as required just by changing m1 and m2, with constant α, as in Fig.3a and Fig.3b. Of course, similar effects result from changing the radial positioning of the eccentric masses. Then, fixed the masses, the axes of the elliptic trajectory, then its inclination, can be set at any value, as in Fig.4a and Fig.4b, by increasing the phase α between m1 and m2 angular positions. This would be a not critical assembly specification, and the machine can be easily adjusted for different material physics. Finally, the concept with two flywheels was rejected because its centrifugal forces generate a resultant moment by the center of gravity, as shown in Fig.5 for the cases of changing the masses aa) or the phase ab). The screen pitching is undesirable, because it adds behavior complications hard to correct in the sequent design stages. The moment for the other concept is not shown because it is always, theoretically, null.

4.2 – Virtual Prototype of the vibrating screen

In the next design stages the best candidate VC is detailed with more refined suspension models. Yet existing commercial suspensions are reused, but here analyzed and

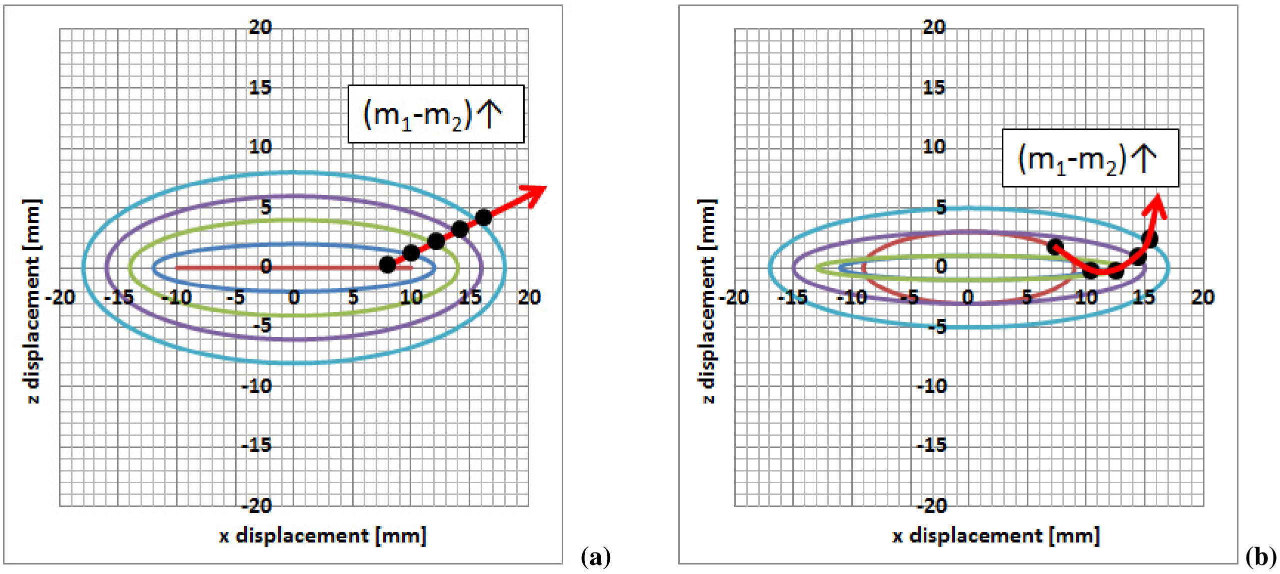

Figure 3: x and z displacements for the two (a) or three (b) flywheels VCs when changing the masses.

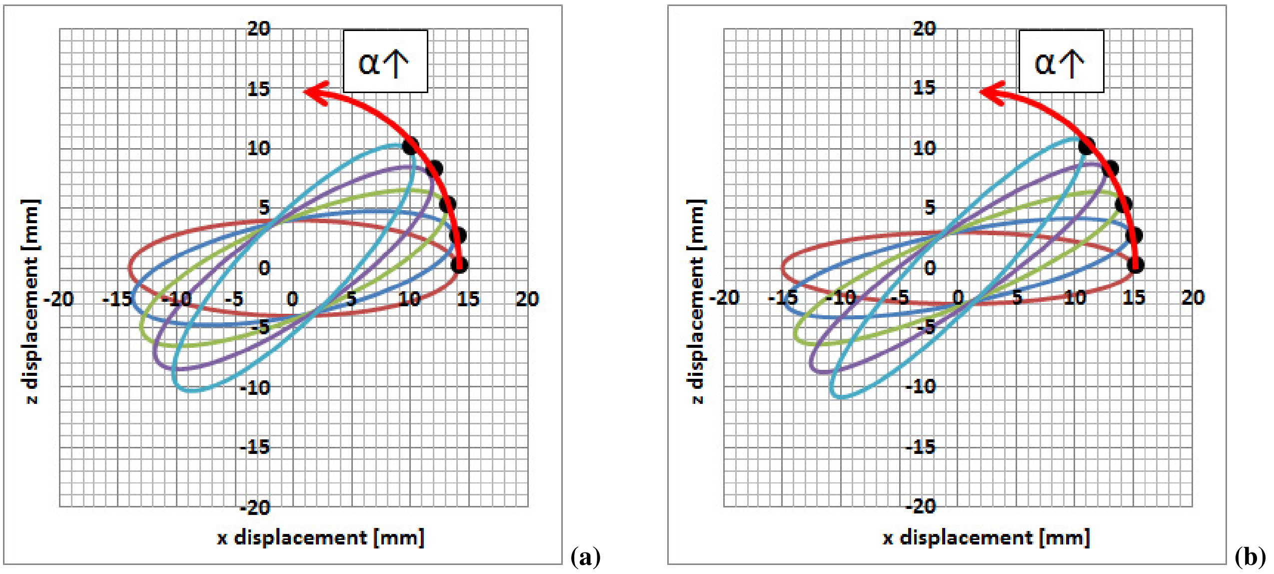

Figure 4: x and z displacements for the two (a) or three (b) flywheels VCs when changing the angle phase

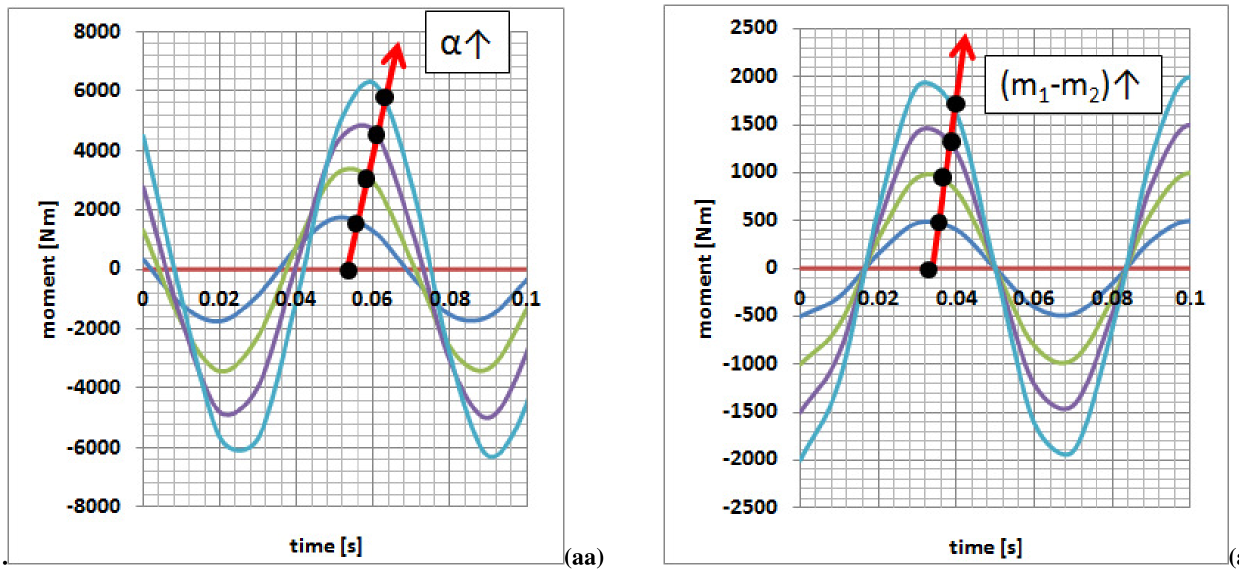

Figure 5: Resultant moment by the center of gravity for the two flywheels VC when changing the masses aa) or the angle phase ab).

simulated one by one by lumped mass, 3D stiffness, damping and initial forces. The transmission shafts are refined with 3D rotational springs to account for the overall deformation for torsional and bending moments.
Translational actuators simulate then the deformations due to differential temperatures by commanding the resulting displacements. These errors are serious for gear teeth engagement, so two refined prototypes are set up. The first prototype uses one gearing and three long shafts to synchronize the wheels, as shown in Fig.6a, while the second has two different gearings synchronized by just one shaft, as in Fig.6b. The second is a little bit more costly, but was finally selected because it results in a much more robust and reliable behavior.
The final evaluations include also the material sieving to adjust the aforementioned masses and phase and to validate the overall behavior. The final resulting trajectories are reported in Fig.7a in case of dry run, easily comparable with the displacements of Fig.7b for the case of material flow. The trajectories of the VP show the same order of magnitude and direction previously obtained by tuning the masses and the phases in the VC, as from Fig.3 and Fig.4. The differences come up from the effects not accounted for in the VC but only in the VP, such as the just mentioned machine interaction with the material flow and the part deformation for torsional and bending moments, forces and differential temperatures effects.
The benefits in introducing the VCs in Sec.4.1 are not easily numerically analyzable. However, the apparently chaotic last charts of Fig.7 give a clear idea of how it would be complicated to absolutely compare the performances of VPs with different architectures, as in the previous Fig.4, without recurring to their simplified VCs. Following the Top-Down design approach, the virtual prototyping analyses are then used to detail the final CAD models, shown in Fig.8.

5- Conclusions

The present paper discusses about the VC modeling for the design of heavy machinery. The VCs should include the main working parameters and boundary conditions in coarse models, saving time and efforts by avoiding detailing the side effects, working errors and noises. The overall performances integration is then evaluated to define one (or few) layout(s) to be passed to the sequent virtual prototyping stage. Here more refined models are included for a much deeper

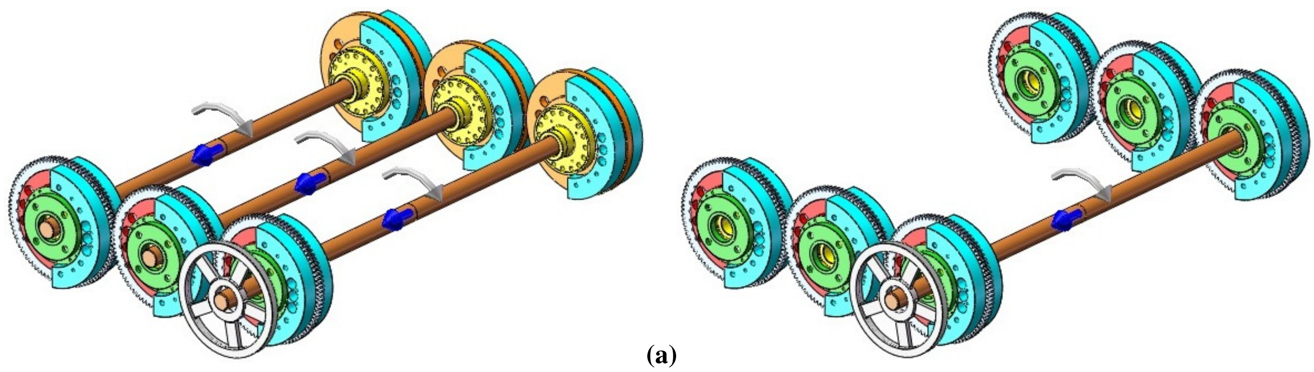

Figure 6: VPs of the vibrating system with the flywheels synchronized by three a) or one b) shafts.

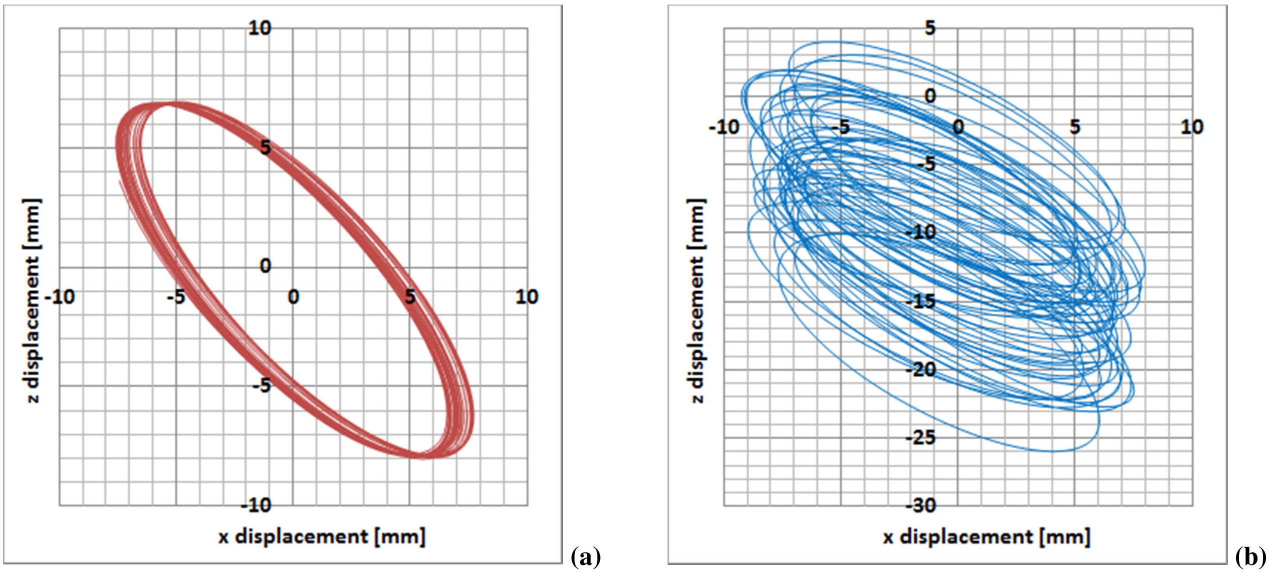

Figure 7: Refined trajectories of the VPs for a dry run a) or in case of material flow b).

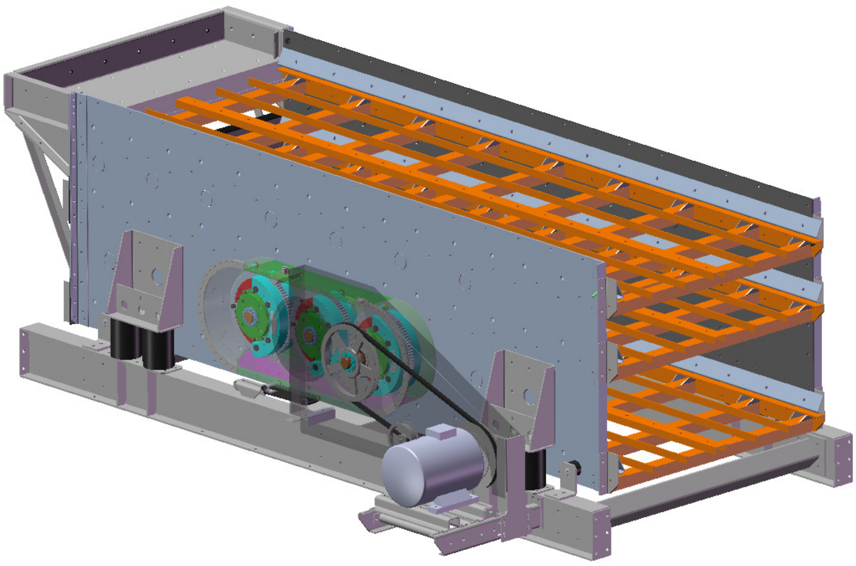

Figure 8: Final model of the vibrating screen.

evaluation. The goal of the VC is to quickly evaluate the different design alternatives to identify the best machine architecture, while the VPs are used to reproduce the actual behavior as deeply as possible. Since many working principles of heavy machinery are achieved with mechanisms motions the integration of the MBD tool within the CAD modeling software is very important to step by step add details to the dynamics model of the VCs, while preserving the possibility to simulate and analyze the results in the whole system.

The first evaluation by simulation opens the way for innovation possibilities by analyzing many different working structure alternatives, without taking it just upon the designer expertise. The VCs simulation is a design method and not just a verification test bench. The main parameters can be optimized with adjustments resulting from the simulation results, and not from trial and error loop steps. Then the virtual prototyping is conveyed and restricted by the passed set of main parameters to reduce the complexity of the great number of variables. The VP also advances some design verifications that were traditionally carried out on real prototypes.

The case study on a vibrating screen for inert materials verified the VC ideas in really designing a machine which undergoes to complex working conditions. The simulations of the VCs showed that the parameters interactions can be noticeably evaluated and tuned, quickly rejecting possible design weaknesses. Then the dynamic VP is less biases prone and can focus on the loads on every part for the dimensioning, fine tuning and verification.

Future works may include more detailed models for the load distribution on the parts, for their deformations and for the material flow for a refined dimensioning and simplification of the machine elements focusing on their durability.

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