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Pushing the Limits: Challenges for Maglev and Hyperloop Vehicle-Guideway Interaction at High Speeds

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Abstract

The high target speeds of Maglev and Hyperloop pose unique challenges for the vibrations of the vehicle and guideway. This paper discusses the nature and importance of two instability phenomena and one instability mechanism relevant to vehicle-guideway interaction. Regarding the wave-induced instability mechanism, we show using simplified models that it is mostly activated at high speeds. It typically gives rise to general oscillatory instability, and it is relevant for both active and passive levitation systems. To suppress the mechanism through guideway and levitation system design, dedicated research is needed, including experimental validation. This is especially important in view of the high target speeds and of the development of slender guideways. Speed and slenderness also necessitate thorough understanding and analysis of the parametric resonance and coupled resonance phenomena. Parametric resonance is an instability type that can occur when the guideway is periodic in space, irrespective of the levitation system type. The size of the instability zones depends on the vehicle speed and on magnitude of the periodic variation: the smaller the guideway's bending stiffness, the larger the support spacing and/or the support stiffness, the larger the zones. To date, the severity of the parametric resonances for realistic systems is far from clear. Regarding the coupled resonance of vehicles and guideways, it is known to occur typically for small vehicle speeds and at standstill, for active levitation systems only. The phenomenon seems to be (a self-excited vibration resulting in) a limit-cycle oscillation, implying that it is not an instability type; it rather occurs when vibrations are already unstable. Detailed investigations should clarify; the outcome may even require the name "coupled

resonance" to be reconsidered. We emphasize that, as it critically depends on the guideway stiffness that typically reduces significantly with increasing speed, the phenomenon may occur at high speeds even when the system is tuned to suppress it at standstill.

Keywords: Maglev, Hyperloop, vehicle-guideway interaction, wave-induced instability, parametric resonance, coupled resonance

1 Introduction

Hyperloop is a potential new transportation mode that is currently under development [1]. Maglev technology is advancing at the same time. The high target speeds of the guided, magnetically levitated vehicles pose unique challenges for the vibrations of the vehicle and the guideway. Generally, both dynamic amplification of vehicle and guideway responses – resonance is an extreme of that – as well as vibration instability (i.e., dynamic instability) are critical points of concern in view of safety, structural integrity and passenger comfort.

Apart from the straightforward and well-documented resonance of guideways (e.g., finite-length or infinite beam) to the action of moving constant and oscillating loads [2,3], vehicle-structure interaction mechanisms are paramount for Maglev and Hyperloop systems. Zhou *et al* [4] and Sun *et al* [5] provided reviews of coupled vibration problems, specifying characteristics along with modelling approaches particularly for systems with electromagnetic levitation; such active systems are probably the most complex ones from the vehicle-structure interaction point of view. The reviews addressed, among other things, the importance of self-excited vibrations ("coupled resonance") at standstill and small speed, and vehicle-guideway interaction resulting from track irregularity, specifically from periodic track irregularity; for both aspects, the flexibility of the guideway turns out to be crucial.

In this paper, we discuss the nature of the coupled-resonance phenomenon along with its relevance for Maglev and Hyperloop. Next to that, we discuss the relevance of the parametric-resonance phenomenon; this phenomenon is often not addressed in vehicle-structure interaction of magnetically levitated vehicles, at least not explicitly. We start the paper with a discussion of the nature and relevance of the so-called wave-induced instability mechanism, which is not widely recognized either in Maglev and Hyperloop vehicle-structure interaction studies. Thus, we address two instability phenomena and one instability mechanism, focusing on high vehicle speeds specifically. The paper provides explanations, initial findings and open questions.

2 Wave-induced instability mechanism

For a vehicle interacting with a flexible guideway, the wave-induced instability mechanism is activated at high speed [6-9]. Energy radiated into the guideway by the moving vehicle is then fed back into vehicle vibration by the guideway's reaction force which, in that situation, is dominated by so-called anomalous Doppler waves that induce guideway vibration. This mechanism is relevant for active and passive levitation systems (i.e., electrodynamic, the hybrid and super-conducting magnet levitation systems), as it is purely mechanical. For systems that are translation invariant (i.e., that have constant properties in space), the mechanism is usually activated above a critical speed for resonance [6,7].

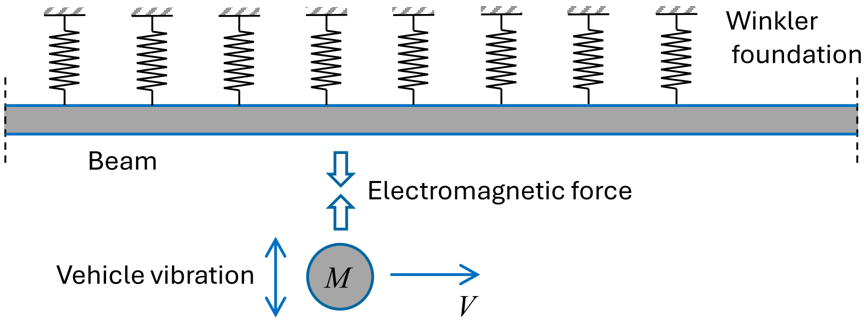

Figure 1: Moving mass suspended electromagnetically from an Euler-Bernoulli beam with Winkler foundation [8].

Fărăgău *et al* [8] investigated the influence of the wave-induced instability mechanism on the stability of a magnetically levitated vehicle considering the simple model of a moving mass (speed V) suspended electromagnetically from an Euler-Bernoulli beam with Winkler foundation; see Fig. 1. A basic PD controller operating on the airgap to stabilize the electromagnetic force was adopted. The stability of the free vibration (about the steady state associated with the gravity) is thus influenced by two state-/response-dependent, potentially destabilizing forces: the guideway's reaction force and the electromagnetic force. Stable (roughly triangular shape) and unstable zones in the plane of control parameters K_p (proportional) and K_d (derivative) were obtained, as shown in Fig. 2. At low speed, the loss of stability is entirely (i.e., along the entire stability boundary) due to the electromagnetic force; this can be shown using energy analysis. As the vehicle speed increases, the triangular stable zone widens, which is due to normal Doppler waves carrying energy away from the vehicle, providing a source of damping to the vehicle vibration (radiation damping); the guideway's reaction force dissipates energy in that case. Close to the critical speed for resonance of the guideway (denoted c_cr in Fig. 2) [2], the widening stops, and beyond that a significant shrinkage of the stable zone occurs; this is due to the anomalous Doppler waves feeding back energy. In fact, the stable zone is even cut into two parts at some speed due to a bending back of the right boundary. Energy analysis confirms that the loss of stability along part of the right stability boundary (relatively small K_d) is due to the guideway's reaction force pumping energy [8]. The exact shape of the stability boundary is governed by the interaction of the two forces; they can be either stabilizing/dissipative or destabilizing depending on the location in the K_p, K_d plane. The *type* of instability along the right boundary is a *general oscillatory instability*, characterized by the oscillation frequency being unknown a priori (the left boundary marks the emergence of a static instability/divergence due to the poorly controlled electromagnetic force and is not addressed any further in the presented results).

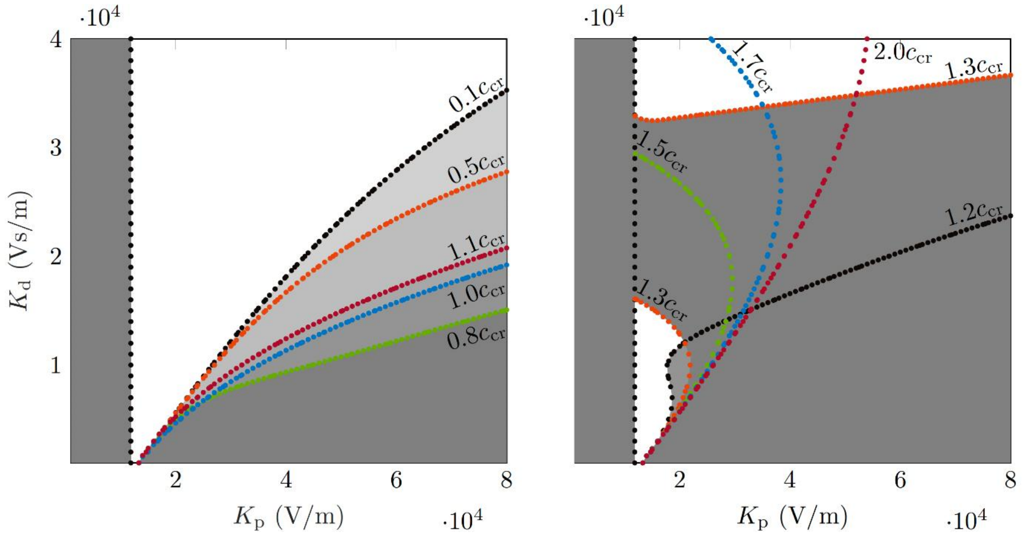

Figure 2: Stable (white) and unstable (grey) zones in the plane of control parameters K_p (proportional) and K_d (derivative) for the model shown in Fig. 1; c_{cr} denotes the critical speed for guideway resonance. Figure has been taken from [8].

We would like to emphasize that the wave-induced instability mechanism also takes place in systems where the support conditions are not constant but vary periodically in longitudinal direction as long as energy can be transferred from one to another periodic cell; that is, when waves can propagate in the system. This is the case when the guideway is continuous, but also when different cells/spans of the guideway are connected through springs, for example. When the guideway consists of a series of fully decoupled girders, the wave-induced instability mechanism cannot occur. However, it is fair to ask how realistic the assumption of complete decoupling is. Adjacent girders in Maglev infrastructure typically share the same supports, and Hyperloop tubes are connected through expansions joins that may provide some stiffness; in either case, energy transfer may happen, which implies that the wave-induced instability mechanism is not excluded, in principle.

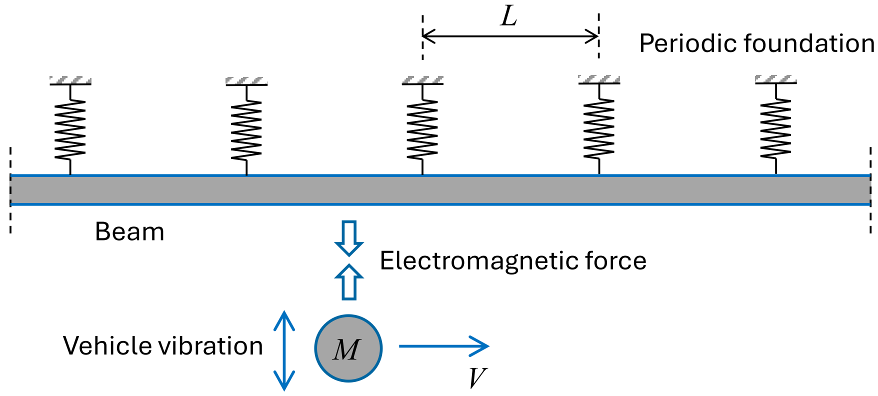

Figure 3: Moving mass suspended electromagnetically from an Euler-Bernoulli beam with periodically arranged discrete-springs foundation [9].

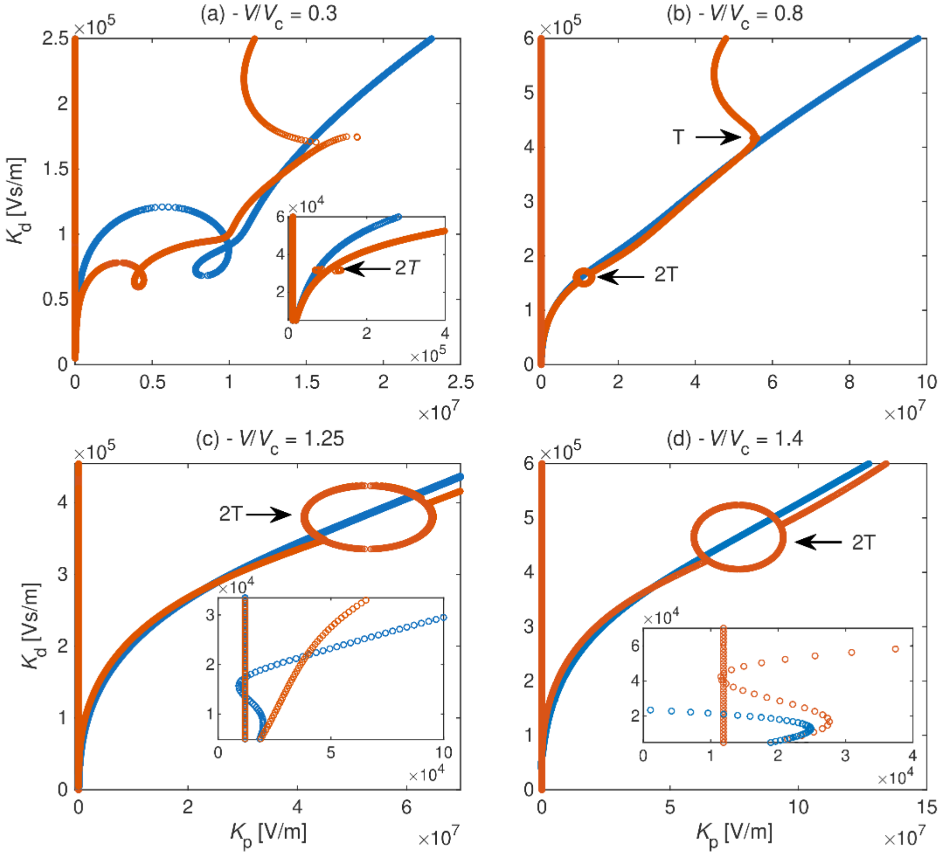

Figure 4: Stability boundaries in the plane of control parameters K_p and K_d for the periodic model shown in Fig. 3 (red curves) and for the (equivalent) non-periodic model shown in Fig. 1 (blue curves); V_c denotes the critical speed for resonance in the latter. Figure has been taken from [9] and slightly modified.

To investigate the influence of the wave-induced instability mechanism in a periodic system, Van Leijden *et al* [9] considered a system similar to that of Fărăgău *et al* [8] (Fig. 1), but with a foundation composed of periodically arranged discrete springs, as shown in Fig. 3. Some typical stability boundaries are shown in Fig. 4, for different speed V of the vehicle and together with the boundaries obtained for the equivalent (i.e., with same support stiffness per unit of length) non-periodic system shown in Fig. 1; V_c denotes the critical speed for resonance in the latter system. Note that the system is stable to the right of the left, straight boundary and to the right of the leftmost right boundary (in some regions, there are different boundaries next to each other on the right side). The stability boundaries obtained for the two models are similar (roughly triangular), but not the same. Elliptical indentations of the stable zone occur, which are related to parametric resonance (see Section 3). Another, amorphous indentation occurs when evanescent waves are excited in the guideway (e.g., see top-right panel of Fig. 4, for large K_p and K_d values), which limit the radiation damping. At high speed, the bending back of the right boundary takes place for the periodic model too (at relatively small K_d), and energy analysis confirms that the loss of stability along that part of the boundary can be attributed to the guideway's reaction force (in other words, to the wave-induced instability mechanism).

One could argue that the wave-induced stability mechanism can be excluded by making the guideway sufficiently stiff, but the question is what the right stiffness and mass need to be. The answer is not so obvious. In periodic systems, anomalous Doppler waves are always excited, but do they do not necessarily lead to instability, as the radiation damping can be more powerful. In the specific case of Fig. 4, the bending back occurs at higher speed than in the non-periodic model, but it is not clear at what speed exactly the anomalous Doppler waves become powerful and activate the wave-induced instability mechanism. Also, for non-periodic systems, the wave-induced instability may even occur without having a true resonance [10].

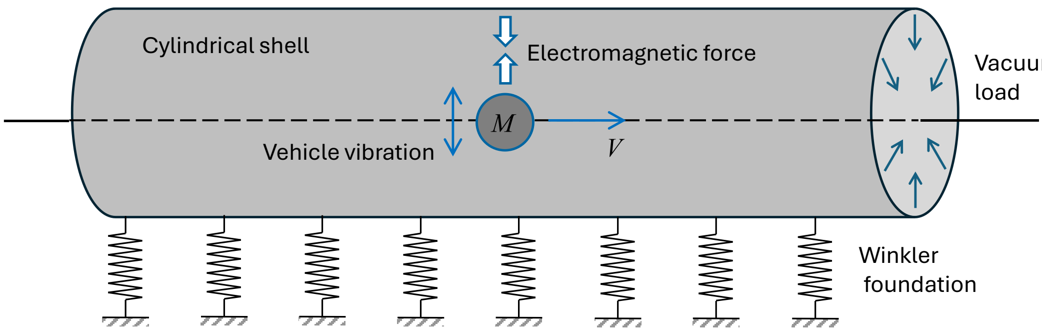

Figure 5: Moving mass suspended electromagnetically from a Flügge shell with Winkler-type foundation [11].

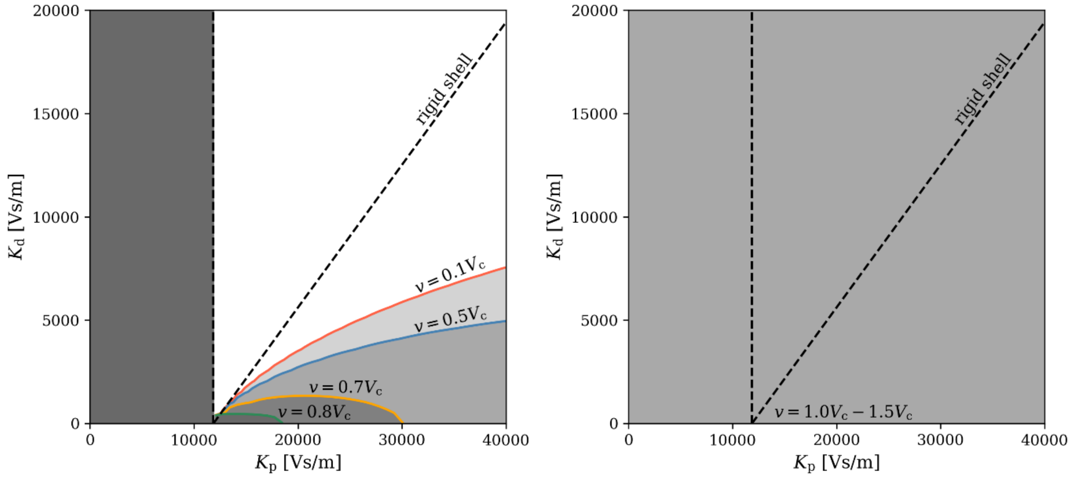

Figure 6: Stable (white) and unstable (grey) zones in the plane of control parameters K_p and K_d for the model shown in Fig. 5; V_c denotes the critical speed for guideway resonance. Figure has been taken from [11].

To investigate the influence of tube/cross-sectional deformations and the presence of pre-stress resulting from the vacuum load on the stability, both relevant for the Hyperloop system, Huber [11] considered the same model as Fărăgău *et al* [8], but replaced the Euler-Bernoulli beam by a Flügge shell; see Fig. 5. Results are shown in Fig. 6. A similar widening of the triangular stable domain is observed for increasing vehicle speed. Interestingly, stability is completely lost in wide speed range beyond the critical speed (denoted V_c). Huber also showed that the critical speed is significantly affected by the pre-stress resulting from the internal vacuum and turns out to be in the operating range of Hyperloop (close to 1000 km/h) when adopting the parameters representative of the European Hyperloop Center (EHC) design [12]; obviously, this claim should be taken with care as the model is only a simplistic representation of the EHC system.

In conclusion, the influence of the wave-induced instability mechanism has been demonstrated using a few simplified models, and its characteristics have been addressed. Clearly, it is mostly relevant at high speed and typically gives rise to a general oscillatory instability, although the mechanism may also be the driving one behind parametric resonance (which is another type of instability) even for small speed; see Section 3. For suppressing/eliminating the mechanism through guideway and levitation system design, dedicated research is needed, including experimental validation. This is especially important in view of the high target speeds and of the development of slender guideway designs, which are required for the cost-competitiveness of Maglev and Hyperloop; slender designs may pose challenges regarding the occurrence and severity of the wave-induced instability mechanism at high speed.

3 Parametric resonance phenomenon

Parametric resonance is a well-known phenomenon occurring in discrete, mass-spring systems with time-periodic stiffness. The most well-known and simple example is that of a single-degree-of-freedom system having a time-periodic spring in parallel to a spring with constant stiffness; the behaviour is described by the so-called Mathieu equation. The additional spring force can destabilize the free vibration of the system depending on the frequency of the variation in relation to the natural frequency of the system without time-periodic spring.

Parametric resonance can also happen in the context of moving load problems when the guideway is a periodic system in space, because the moving object, when travelling at constant speed, experiences a time-periodic variation of the support structure. The phenomenon may occur for both passive and active levitation systems. The potential importance for Maglev applications was already recognized by Cai *et al* [13,14], and initial studies for purely mechanical systems have been conducted [15,16]. As indicated in Section 2, for the model shown in Fig. 3, zones of parametric resonance occur, which have an elliptical shape; see Fig. 4. Along the elliptical indentations, the fundamental period of the motion is known a priori (contrary to the case of general oscillatory instability) and is either the same as the period of variation of the system ($T = L/V$, with L denoting the support spacing and V the vehicle speed) or twice that period ($2T$). The size of the ellipses can be much larger when the periodic inhomogeneity/variation is stronger; i.e., when the bending stiffness is decreased, the support spacing and/or the support stiffness is increased [9]. Furthermore, it is important to realize that parametric resonance can also take place for relatively small velocities, as shown in Fig. 4 and occurs irrespective of the bending back of the right boundary addressed in Section 2.

To explore the severity of parametric resonance for Hyperloop, Gatt [17] considered the model of Huber [11] (Fig. 5) with the Winkler foundation replaced by a periodic foundation (Fig. 7). Initial results are shown in Fig. 8; note that other parts of the stability boundary are not included (i.e., parts related to general oscillatory instability). For parameter values representative of the EHC, the zones of parametric resonance appear rather limited in size (except for speeds $V \gg V_c$, beyond the operating range of Hyperloop), which is probably because of the high stiffness of the structure of the EHC; for larger-diameter tubes, tinner tubes and/or longer spans, the zones may be much larger. Again, we note that the model is a simplistic representation of the EHC system, as many features, some of them occurring periodically (e.g., low-stiffness expansion joints and tube stiffeners), are still not included.

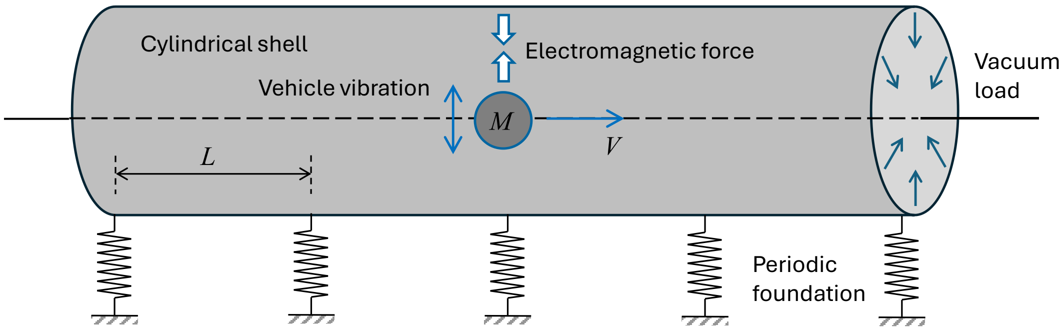

Figure 7: Moving mass suspended electromagnetically from a Flügge shell with periodically arranged discrete-springs foundation [17].

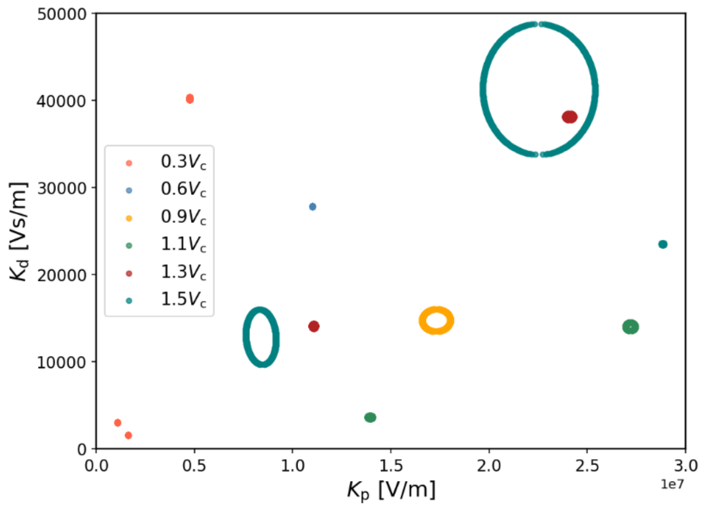

Figure 8: Parametric resonance zones obtained for the model shown in Fig. 7. V_c is the main critical speed for guideway resonance. Figure has been taken from [17].

We note that parametric resonance is a *phenomenon*, and more specifically, a *type* of instability. The underlying *mechanism* providing the energy can be different; the loss of stability can be due to the electromagnetic force or due to the guideway's reaction force, in principle [9]. We also underline that the phenomenon will still be there when the guideway consists of a series of fully decoupled beams. As discussed in Section 2, the wave-induced instability mechanism is not active then, but the moving vehicle will still experience a time-periodic support structure. Hence, analyzing a single beam interacting with a moving vehicle [e.g., 18] is not sufficient for the analysis of vehicle-structure interaction for Maglev and Hyperloop.

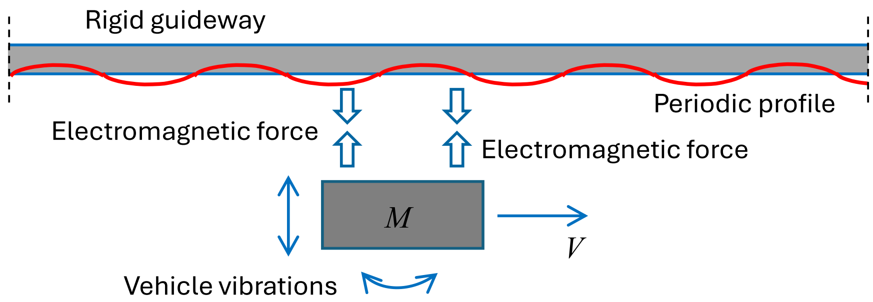

Figure 9: Moving vehicle suspended at 2 points electromagnetically from a rigid guideway with a periodic profile [20].

To illustrate that parametric resonance still occurs when the wave-induced instability mechanism is excluded, we consider the limiting case of the support structure being rigid but having a periodic profile, and a levitated vehicle having one or two degrees of freedom [19,20]; the model for the latter is shown in Fig. 9. Both simple and combination parametric resonances were found (graphical findings are not presented here), all of them creating elliptical indentations of the otherwise triangular stable domain (cf. Fig. 1). Combination parametric resonance was found to be the most severe.

In our view, a comprehensive study is needed to assess the importance of parametric resonances for Maglev and Hyperloop, especially when vehicle speeds will be increased and/or when more slender designs will be considered (as indicated in Section 3). Parametric resonances may pose important challenges to guideway and control system design.

4 Coupled resonance phenomenon

For Maglev systems that employ steel structures, violent vibrations of the vehicle and infrastructure have been reported for small vehicle speeds and at standstill [4,21], particularly in low-stiffness areas [5]. The vibrations only take place for active levitation systems such as the electromagnetic and hybrid systems [4]. The phenomenon is referred to as "coupled resonance" or "vibration resonance phenomenon" [4,5,22], and it has even been related to parametric resonance [4]. The phenomenon was also observed in experiments at the EHC with the vehicle at standstill and at low speed; these experiments were conducted as part of the HYSPEED project [23]. Fig. 10 shows a typical tube response. The occurrence critically depended on the vehicle position, confirming that the infrastructure stiffness plays a significant role.

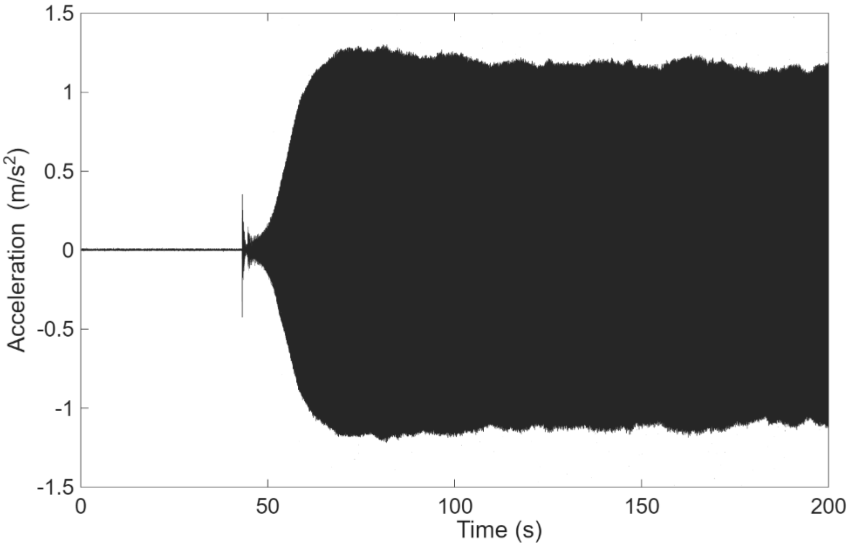

Figure 10: Violent vibrations of the EHC infrastructure (at top of the tube) when interacting with an electromagnetically levitated vehicle at standstill.

In our view, the claim of the phenomenon being related to parametric resonance is incorrect. In the limiting situation of the vehicle at standstill, it does not experience a time-periodic support structure, hence parametric resonance cannot occur (see Section 3); the system is simply time invariant. For small vehicle speed, the same vibrations are observed, which suggests that the phenomenon is not related to parametric resonance at all (also note that the parametric excitation is very weak at small speeds). On the other hand, referring to the violent vibration as a self-excited vibration seems right [4,5]. Preliminary modelling (no details shared here) has shown that the occurrence of the vibration critically depends on control settings; model predictions show the occurrence of a so-called limit-cycle oscillation when the control settings are chosen just outside the stable domain. A limit-cycle oscillation is a steady oscillation with significant amplitude that typically occurs when the free vibration is initially (i.e., for small amplitudes) unstable; the response remains bounded and develops into the steady oscillation due to the nonlinearity of the system getting activated at growing amplitudes. If the coupled resonance is indeed a limit-cycle oscillation, the phenomenon is not an instability *type* (like parametric resonance) but rather a phenomenon that occurs when the free vibration is unstable.

More detailed investigations into the coupled resonance are needed. The name may even have to be reconsidered based on insights to be developed. Question is whether the phenomenon is indeed (a self-excited vibration resulting in) a limit-cycle oscillation. Literature states that it occurs when certain frequencies come close [5], which makes the vibration particular. Furthermore, we would like to emphasize that, as the emergence of the coupled resonance critically depends on the guideway stiffness, its relevance for high vehicle speeds needs to be explored. The reason is that the stiffness of the guideway as perceived by a moving object typically reduces significantly with increasing vehicle speed, and a critical stiffness (for the coupled resonance to happen) may be reached even when the stiffness of the structure is tuned to exclude the coupled resonance at standstill. New insights to be developed will serve guideway and control system design.

5 Conclusions

In this paper, we discussed the nature and relevance of two instability *phenomena* and one instability *mechanism* for Maglev and Hyperloop vehicle-guideway interaction, focusing on high vehicle speeds specifically.

The wave-induced instability mechanism is relevant to all levitation system types (active and passive), as it is a purely mechanical mechanism. It is mostly activated at high speeds and can only occur in guideways with coupling between the different spans. It typically gives rise to a general oscillatory instability (with oscillation frequency unknown a priori), although the mechanism may also be the driving one behind the phenomenon of parametric resonance. We demonstrated the influence of wave-induced instability mechanism using a few simplified models and addressed its characteristics. For suppressing/eliminating the mechanism through guideway and levitation system design, dedicated research is needed, including experimental validation. This is especially important in view of the high target speeds and of the development of slender guideway designs, which are required for the cost-competitiveness of Maglev and Hyperloop. Slender designs and high speeds also necessitate thorough understanding and analysis of the parametric resonance and coupled resonance phenomena.

Parametric resonance is an instability type that can occur in the context of Maglev and Hyperloop when the guideway is a periodic system in space, because the moving object, when travelling at constant speed, experiences a time-periodic variation of the support structure. The phenomenon may occur for active and passive levitation systems. The size of the parametric-resonance instability zones depends on the vehicle speed and on magnitude of the periodic inhomogeneity/variation: the smaller the guideway's bending stiffness, the larger the support spacing and/or the support stiffness, the larger the zones. It is noted that parametric resonance does not only take place for high vehicle speeds. Also, both simple and combination resonances can occur, and the latter may be the most important ones. We emphasize that, to date, the severity of the parametric resonances for realistic Maglev and Hyperloop systems is far from clear.

The violent vibrations of Maglev and Hyperloop vehicle and infrastructure that have been reported for small vehicle speeds and at standstill are typically referred to as "coupled resonance" or "vibration resonance phenomenon". Such vibrations only happen with active levitation systems. In our view, the claim of the phenomenon being related to parametric resonance is incorrect. Referring to it as a self-excited vibration seems right; initial analyses indicate that the phenomenon is indeed (a self-excited vibration resulting in) a limit-cycle oscillation. If that is confirmed, it is not an instability type (like parametric resonance) but rather a phenomenon that occurs when free vibrations are already unstable. More detailed investigations should clarify its nature. Literature states that the phenomenon occurs when certain frequencies come close, which makes the vibration particular. We emphasize that, as the emergence of the vibration critically depends on the guideway stiffness, the relevance for high vehicle speeds needs to be investigated. The stiffness of the guideway as perceived by a moving object typically reduces significantly with increasing vehicle speed, and a critical stiffness (for the coupled resonance to happen) may be reached even when the stiffness of the structure is tuned to exclude the coupled resonance at standstill.

Acknowledgements

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