ATTENUATION OF TRANSMISSION OF VIBRATIONS AND GROUND-BORNE NOISE BY MEANS OF STEEL SPRING SUPPORTED LOW-TUNED FLOATING TRACKBEDS

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1. INTRODUCTION

In the Spanish city of Barcelona a hospital is currently being built supported on steel spring elements. This vibration isolation measure became necessary because the hospital is constructed wall to wall with an existing metro line. If the rail track had been planned and built subsequently, the trackbed would have had to be isolated. With regard to this particular situation, a high-performance floating trackbed would have been required. Then the steel springs would support the trackbed (source) instead of the hospital (receiver).

In congested areas, the close vicinity of rail tracks to buildings and structures and thus to people or sensitive facilities often leads to conflict in respect of the transmission of noise and vibrations. Protection can be provided by the deployment of vibration isolation systems either to the source or to the receiver. Regarding the first case, there are quite a number of techniques available. However, in many cases the best performances can be expected from low-tuned floating trackbeds with steel springs.

This paper illustrates different floating trackbed systems and shows their main characteristics and design aspects. Construction features are mentioned as well as the installation of the elastic interfaces.

2. VIBRATION ATTENUATION MEASURES

Noise and vibrations spread by rail tracks are mainly generated by the contact between wheels and rails. In the long run rail corrugation and deformation of wheels are almost unavoidable. A great deal of maintenance is required to keep the quality of the contacting surfaces within acceptable limits. The periodical grinding of rails in long track sections within sensitive areas is as expensive as the after-treatment of the wheels. Finally the application of other vibration attenuation measures may be more practicable and cost saving. Quite a number of techniques have been developed which differ significantly in efficiency and costs. Rail and baseplate pads mainly provide elasticity to the track as especially required in the case of a slab track system rather than reduce noise and vibration radiation. In this respect other systems like embedded rails or ballast mats can be expected to be more effective but at a higher cost.

3. FLOATING TRACKBED SYSTEMS

There is no doubt that the best performances in terms of vibration attenuation can be achieved by floating trackbed systems if they are well designed by experienced engineers. These mass-spring-systems (MSS) consist of floating slabs with the rails mounted on top. The slabs are usually constructed of massive concrete. Together with the dead load of rails, sleepers and fastenings (and the ballast, if any), they form dynamically active masses which are isolated from the sub-structure by elastic mounts which may be of rubber, elastomeric material or steel.

The performance of a MSS depends on a number of factors. Besides the vertical tuning frequency the bending natural frequencies of the slabs are of significant importance. In addition, the system damping as well as the stiffness of the sub-structure have a clear influence. Finally, the success of a MSS can also depend on the dynamics of the tunnel itself. In certain cases there is little advantage to be obtained by using a medium-frequency (say above 15 Hz) floating-slab track construction in railway tunnels [1].

Since the tuning frequency depends on the static spring deflection, it is obvious that the spring stiffness is the most important issue. Fig.1 shows the transmissibility factor V_F over the tuning factor η. The tuning factor is defined as the ratio of the excitation frequency f divided by the natural frequency f_z. It clearly shows that attenuation of vibration transmission takes place only if the factor is beyond the value of $\sqrt{2}$ .There is no reduction of dynamic forces possible when the natural frequency (= tuning frequency) of a MSS is close to or above the relevant excitation frequencies.

Typical vibration frequencies induced by trains are found in a range of 10 - 80 Hz. The frequency spectra usually reveal a concentration of higher peaks in the 60 Hz area, e.g. due to natural frequencies in the bogie system. However, quite often there are high vibration levels between 10 and 30 Hz as well (see Fig.2).

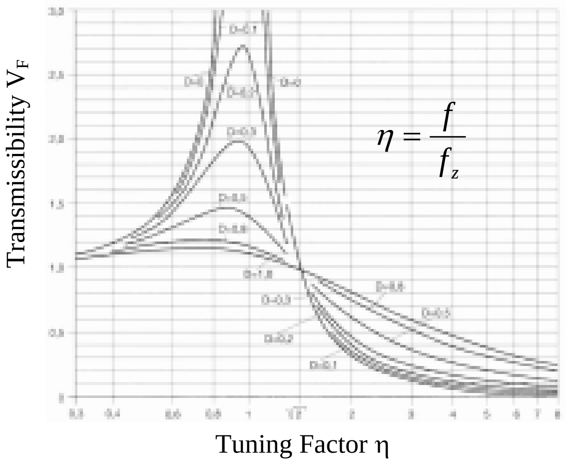


Fig.1 Transmissibility V_F versus tuning ratio η for a single-mass-system with constant frequency excitation.

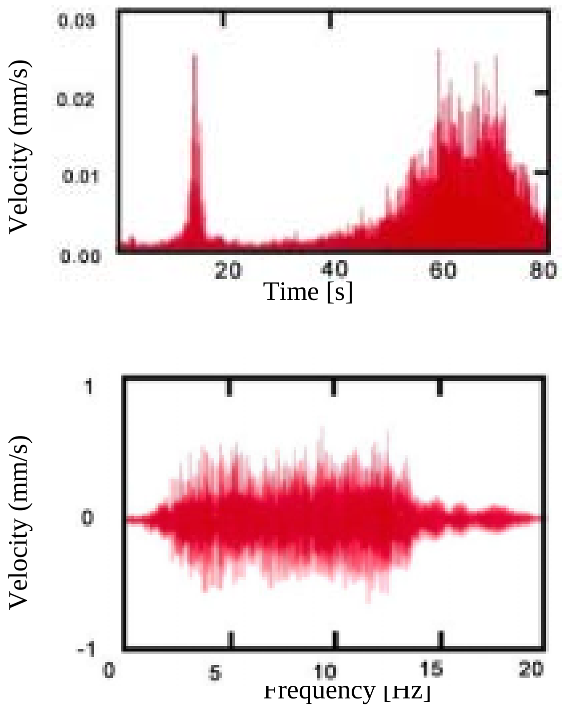


Fig.2 Vibration readings of a passing train

In the case of a standard trackbed, these frequencies might cause severe vibration problems in nearby buildings showing resonance frequencies just in that range. Even a MSS with a tuning frequency as low as 10 Hz would not provide sufficient mitigation. And things go from bad to worse, when a costly MSS, designed to a 10 Hz tuning frequency, actually shows 12 - 15 Hz which would then be close to resonance. The only solution for this scenario is to choose a so-called ' low-tuned ' mass-spring-system. Steel springs can be relied on to provide a tuning frequency below 7 Hz.

Since the tuning frequency of a floating trackbed is so important, it has to be explained how it is defined. As a first approach, the extension of the slab can be neglected and all spring stiffnesses of a direction can be united as one common spring. This results in a single-mass-system with 6 degrees of freedom. With respect to the direction of the dominant train excitations, here the vertical translation natural frequency is the most relevant one here referred to as the 'tuning frequency'. A linear spring elasticity provided, the tuning frequency of the non-damped system can easily be calculated by the following simplified equation:

$$f_z = \frac{5}{\sqrt{\delta_{[cm]}}}(Hz) \qquad \text{with} \quad \delta = \frac{F}{k_z}$$

F = load force, k_z = vertical spring rate

Although the actual correlations are much more complex, the tuning frequency can be used to evaluate the efficiency of a floating trackbed system at a first view. Sometimes the non-suspended part of the rolling stock is added to the mass leading to a lower tuning frequency. This part is usually chosen at 1/3 of the axle loads contributing to the sprung system.

However, more realistic results will be achieved by modelling the slab according to the Finite-Element-Method (FEM). In this case the flexural modes of the slab are taken into consideration. This is of special importance when the 1.order bending natural frequency of a slab is in the same range as the tuning frequency. The result is coupled modes with the tuning frequency shifted and a diminished tuning factor which might result in a reduction of the isolation efficiency of the system.

3.1. Slab Length

The length of the slabs remains an issue. Floating slabs have been built with lengths from less than one up to several hundreds of meters. Short slabs can be prefabricated elsewhere. They can easily be moved and are favourable in terms of a fast track laying. Their lowest flexural frequency can be designed safely beyond the relevant parts of the excitation spectrum. However, the high number of joints may create problems. A chain of short slabs does not possess a common stiffness, even if the slabs are connected by shear dowels. The full dynamic and static load of an axle or bogie has to be taken by a single slab with almost no spread of loads to the neighbouring slabs. With regard to the connecting rails, translatory and rotatory displacements have to be limited. For this reason they have to be either very massive or they must be placed on comparatively stiff mounts. The latter might result in an unfavourable high tuning frequency. Last but not least, shifting of a slab might occur due to lack of inertia mass requiring horizontal restraints, which are especially required when the elastic mounts are soft in the horizontal direction.

Medium size slabs with their lengths in a range between 5 m and 20 m are often of little advantage. If prefabricated, they may be too heavy and bulky for transport on site, especially in tunnels. The number of joints remains high. Depending on the slab thickness the relevant flexural frequencies may be close to resonance. If built in-situ the high number of slabs may increase construction time and cost.

The longest possible slabs are usually the ones preferred. Built in-situ, the slabs will always fit into the tunnel shape. The inertia forces of the large mass prevent shifting. The number of joints can be reduced to a minimum. However, there usually is a certain limit in length due to temperature expansion. At moderate slab thickness, their lowest bending natural frequencies are far below the relevant spectral values. Actually they do not appear on the frequency list since they usually are coupled with the dominating tuning frequency. Fig.4 shows typical vertical bending modes of 2 slabs, both with a length of 30 m and tuned to 6 Hz, but with different slab thicknesses at 0.40 and 1.20 m:

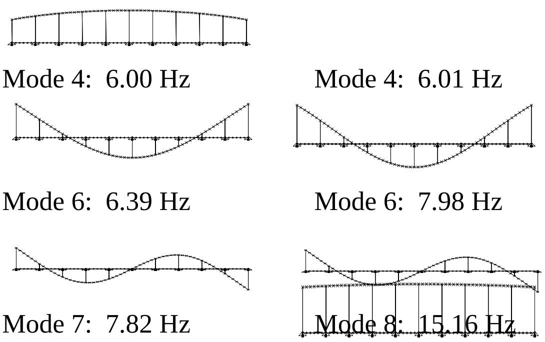


Fig. 3a Slab thickness at 0.40 m

Fig.3b Slab thickness at 1.20m

3.2 Floating Trackbeds on Steel Springs

Since the beginning of the nineties, GERB have been successfully developing floating trackbeds on coil springs. They can be designed for all types of permanent way and for all axle loads.

Tuned to a frequency as low as 5 - 7 Hz, they have proved to be most efficient and most reliable especially in the low frequency range. Beyond an excitation frequency level of 20 Hz high attenuation values up to 15 - 25 dB are expectable. They are a classic application at nearby buildings having their relevant floor resonances between 10 and 30 Hz.

With respect to the particular situation, they can be constructed as a ballast trough or a massive concrete slab. Slabs require a comparatively flat thickness of just 300 - 600 mm thus saving space and construction material. Except in cases of high seismic loads, horizontal restraints are not required due to the high horizontal stiffness of the steel springs.

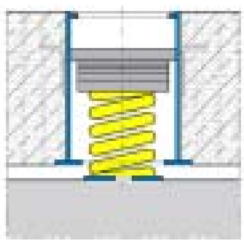
GERB, the German based engineering company, is a specialist in vibration control. They have been dealing with coil springs used on mass-spring-systems for almost 100 years.

3.3. Steel Spring Elements for Floating Trackbeds.

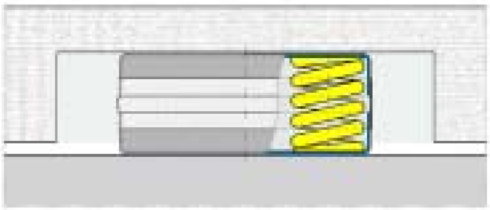
Mass-spring-systems are always tailored structures. In general, the local situation and the dynamic and static requirements determine the cross section of the MSS. The overall construction costs are significantly influenced by the method used to lift the slabs and to place the bearings in position.

For MSS installation with elastomeric mounts quite a number of different installation methods have been developed. Precast slabs are usually placed directly on top of the mounts which often require an extra plinth of grout to compensate for tolerance deviations in the sub-surface. In-situ slabs sometimes require expensive hoists to be lifted or a large number of manholes arranged close together with lateral recesses to provide jacking space. These manholes reduce the slab mass, weaken the slab stiffness, require extra formwork and reinforcement, and finally need a cover softly supported to avoid rattle.

GERB steel spring elements provide several advantages saving cost on the construction side which compensates for the higher primary cost. They may be different in the construction and in the number of springs contained. The housings are designed to different purposes and applications. The elements are either embedded in the slabs or arranged laterally depending on the availability of access.



a) GSI(V)-type element embedded in the slab



b) KY-type element laterally inserted

Fig.4 Spring elements for floating-slab tracks

GSI(V)-type steel spring elements are used when there is no lateral access to the slabs. This is a usual situation in a bored tunnel. The element comprises 3 principal parts: The housing, the coil spring unit and a mechanism for height adjustment. The housing is embedded in the concrete slab which is supported by a base ring. The top of the housing is closed with a cap to prevent dirt and other material from entering the element. The actual elastic element, the coil spring, sits on the sub-structure (e.g. the tunnel invert). A hydraulic cylinder is used to compress the springs resulting in the uncomplicated lifting of the slabs off the sub-structure.

KY-type steel spring elements are inserted into recesses arranged laterally in the slabs or troughs requiring access space on both sides. Initially, the slab is lifted-up by 70 - 100 mm by means of hydraulic jacks. Because of their higher load capacities, the elements can be arranged at larger distances (3 - 8 m) depending on the slab stiffness. In stations with elevated tracks the elements can be concentrated favourably on top of columns or above supporting beams.

Both element types are accessible for inspections at any time, either from above or from the side. Subsequent readjustment of vertically deviated track levels is possible by shimming. They can be provided with a damping system to improve the transmission loss at higher frequencies. The system damping can be 5 - 10 %. Their dynamic behaviour is the same since they contain the same types of springs. The springs are designed to acknowledged standards with clearly defined stiffnesses for all directions. The linear load/deflection curve and the conformity of static and dynamic stiffness are further positive issues. All the springs are fatigue-proof. There is no settlement. Maintenance is not required. An excellent anti-corrsion system guarantees a long lifetime.

4. EXAMPLES OF FLOATING TRACKBEDS ON STEEL SPRINGS

4.1 A Trough-Type Floating Trackbed

A trough system with a ballast trackbed supported on steel springs was installed and completed in 1997 at Puchon Station in Seoul/R.of Korea. In order to protect the shops and offices inside the station building from noise and vibration caused by the 22 t-axle load freight trains, the 6 track sections with an extension of 210 m each were isolated by a 6 Hz mass-spring-system (without train loads). Each section consists of 6 troughs with a length of up to 45 m. Fig.6 illustrates the typical system cross section.

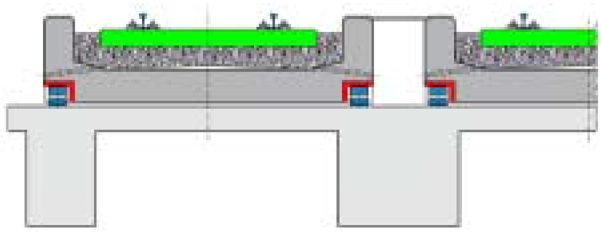


Fig.5 Cross section of the 6 Hz floating trackbed at Puchon Station

In this case lateral access to the troughs allowed the application of cost saving KY-type spring elements especially developed by GERB to this purpose. After lifting of the troughs being manufactured directly on top of the substructure by means of hydraulic jacks, the spring elements were laterally inserted into the recesses used also for the temporary installation of the jacking system. Then the ballast bed, concrete sleepers and rails were installed.

Fig.6 Trough elevation with laterally arranged spring elements

Demonstrated by measurements the tuning frequency proved to be 5 Hz (including train loads). This was an essential aim of the measure since the wide-span slabs of the substructure show natural frequencies at about just 12 Hz

4.2 A Slab-Type Floating Trackbed

In Cologne/Germany a bored tunnel was built to operate a section of the city light rail transit system under ground. Due to the close distance of the tunnel to the foundations of residential buildings, complaints by the residents about vibration and noise had to be anticipated. A maximum of vibration mitigation was required. Experience with other measures like e.g. the Cologne Egg have revealed their limited efficiency. Finally the decision was made on a high-performance, 6 Hz floating-slab track with steel springs to be installed in the 2 single-track tunnels at a length of 900 m each.

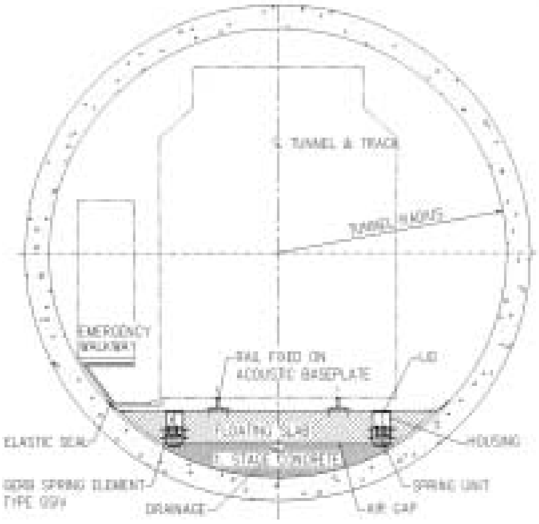


Fig.7 Tunnel cross section

The tunnel has an inner effective diameter of 5.60 m. The 30 m concrete slabs are 400 mm thick and supported on GSI(V)-type spring elements embedded in the slabs. The slabs are entirely separated from the tunnel structure by a 30 - 40 mm air gap. They are not linked by shear dowels. The rails are fixed to elastic fastenings bolted on top of upstands which are also used for canting at curves. The design axle load is 10 t.

The construction of the MSS was quite simple and cost saving. After a bond-breaking PVC-layer was spread over the tunnel invert and the adjacent bottom areas of the tunnel walls, the spring housings were placed according to the drawing. At this point in time the still empty housings are closed at top by a cap. When the steel reinforcement was installed, the concrete was poured to the upper rim of the housings. Once the concrete had gained sufficient strength the slabs were ready to lift. With a compact and handy tool including a hydraulic jack the springs were stepwise compressed, one after the other, until the slabs were lifted from the bottom. Steel shims were used to achieve the correct slab level. The spring deflections were measured and corrected where required to ensure the design tuning frequency and thus the dynamic performance of the system.

At both ends of the floating-slab track section the number of springs were gradually increased to achieve a smooth adjustment of stiffness at the transition to the conventional trackbed. By arranging the elements outside the areas of the fastenings and the rails, the springs were rendered accessible at any time. Although maintenance is generally not required, it will always be possible to perform inspections. In a quite unusual case of a spring failure, the spring can easily be replaced within minutes. This technique also allows fast track adjustments in the case of smaller tunnel settlements.

The successful performance of the MSS was proved by measurements. Other successful installations of the same system are in tunnels in London/UK (DLR line), Stuttgart/Germany (at Ruit station), Sao Paulo/Brazil (Line 3), City of Brasilia(Brazil). Another installation is under construction in Tokyo/Japan.

4.3 A Slab-Type Floating Trackbed above Ground

A tram passing in front of a Hotel in the city of Bielefeld/Germany caused non acceptable vibrations inside the old building. A switch made the situation worse. It was decided to isolate the track from the ground by means of steel springs. The MSS was tuned to 5 - 6 Hz.

A 60 m long slab of a 600 mm thickness was designed to support the track including the switch. On top asphalt was laid since the slab is part of a street used by car traffic as well. The slab is supported on integrated GSI(V) elements and embedded in a shallow concrete pit. Sealing of the gaps between slab and pit walls and a suitable drainage prevent flooding of the pit.

The concrete slab, constructed on top of the bottom slab of the pit, was lifted stepwise by means of a hydraulic jack applied to the springs. Trams had already started operation again when the final adjustments were done. The vertical spring deflection due to the tram passage is about 3 mm.

Fig.8 Tram passing over a floating slab

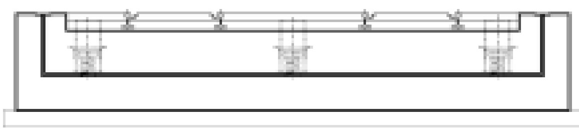


Fig.9 Floating trackslab arranged in a shallow pit at ground level

Similar floating-slab tracks were successfully built at 2 locations in Frechen, a small town near Cologne/Germany. The reasons again were the high vibration levels caused by trams when passing over switches.

5. MEASUREMENT RESULTS

Measurements were performed inside the Cologne tunnel on top of the floating slabs as well as on the tunnel walls [2]. The objective was to gain information about the efficiency of the MSS and the behaviour of the slabs on train passage.

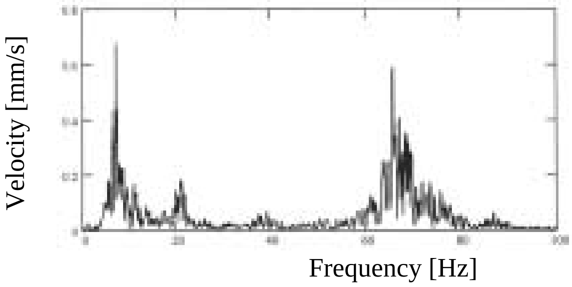


Fig.10 Narrow band spectrum up to 100 Hz on top of the floating slab

The results obtained on the slabs (Fig.10) clearly show 3 ranges of significant frequencies. There are several frequencies standing out at 7 -8 Hz related to the tuning frequency and the lower bending natural frequencies of the slabs. Frequencies between 20 and 25 Hz are caused by the difference in stiffness at and between the rail fastenings. They are related to the spacing of the fastenings and to the speed of the train. At a spacing of 0.6 m the frequencies show a train speed between 44 and 54 km/h. Frequencies in the 60 Hz range can be traced to higher system modes as well as to natural frequencies of the bogies.

The slab reactions can be described as follows: Firstly, flexural waves run in front of the train over about one slab length responding to vibration energy propagated along the rails. The tuning frequency of the slab is also excited. When the train enters the slab these vibrations are immediately calmed down and superseded by higher frequencies excited by the wheel-rail contact. After the train passage the coupled frequencies are dominant again. The decay shows a damping value of 2 - 5 %.

The results obtained on the tunnel wall show no vibration signals differing significantly from the backround vibrations. However, the frequency spectrum reveals characteristic ranges congruent with the ones on the slabs but at lower vibration levels. This fact obviously demonstrates high transmission losses which could be determined in the vertical direction between 45 and 60 dB within the 20 - 400 Hz range.

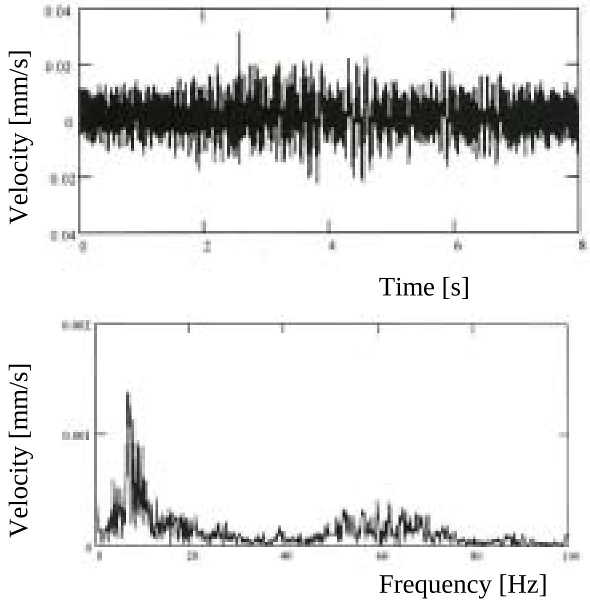


Fig 11 Time signal and frequency spectrum, recorded on the tunnel wall adjacent to the slab

In Bielefeld velocities were measured on top of the isolated slab as well as next to the slab and next to the adjacent conventional ballast bed. Attenuation values were recorded up to 25 dB between 12 and 100 Hz. The design tuning frequency of 5 - 6 Hz was confirmed. To the satisfaction of the owner the vibration level inside of the hotel was proved to be below the threshold of human perception.

6. CONCLUSION

With well designed, low-tuned floating trackbeds, high vibration attenuation levels can be reliably achieved. Supported on steel springs, long slabs or troughs provide advantages in terms of construction, installation and performance. Several applications are shown. The springs are generally accessible. They allow the fast and easy readjustment of deviated track levels. Being fatigue-proof and provided with an excellent anti-corrosion system, the springs are designed to a long lifetime.

REFERENCES

[1] Hunt,H.E.M., "Measures for reducing ground vibration generated by trains in tunnels." In:.*Noise and Vibration from High-speed Trains*, ed V.V.Krylov, Telford, 2001, Chapter 14, pp423-430

[2] Jaquet,T. and Hueffmann,G. "Ausbildung eines tieffrequenten Masse-Feder-Systems mittels Stahlfederelementen bei U- und Vollbahnen als Schutz gegen Erschuetterungen und Koerperschalleinwirkungen", *VDI Berichte Nr.1345* (1997) S.143 - 160