VIBRATION CONTROL SYSTEMS FOR TRACKBEDS AND BUILDINGS USING COIL STEEL SPRINGS

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1. Abstract

In congested cities the number of railway lines has rapidly increased. The close vicinity of rail tracks to buildings often gives rise to conflict in respect of the transmission of noise and vibration to people or sensitive equipment. Vibration attenuation can be safely achieved by well designed vibration control systems applied preferably to the source but also to the receiver. In both cases, the installation of an elastic interface effectively reduces the transmission of vibration. Here, the support of either the rail track or the building on coil steel springs has proved to be a highly-effective and reliable measure. The paper deals, at the beginning, with the description of some floating slab variants based on different steel spring elements. Then some examples of elastically supported buildings are shown. The paper refers to layout and design as well as to installation and construction features and considers the efficiency achievable by these measures.

2. Introduction

Buildings located in the close vicinity of rail tracks are very often subject to the transmission of vibration (Fig.1). As a result, low-frequency (mechanical) vibration and structure-borne noise may annoy the residents inside the buildings or impair its use possibly lowering the value of the building significantly. At the planning stage, structural vibration attenuation measures at a building are often possible but usually lead to undesirable modifications in the architectural design. The deployment of an elastic interface within the vibration transmission line has proved to be a most efficient and reliable measure.

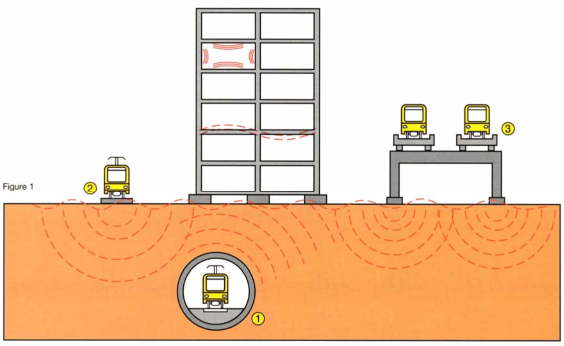

Fig.1 Environmental impacts

Today, two fundamental solutions are generally available: The isolation of either the rail track or the building. Both solutions are efficient and reliable in a comparable way.

The question about who is in charge of undertaking such attenuation measures usually can be answered quite simply. It is the one who either plans a building adjacent to an already existing railway track or, vice versa, a track adjacent to an existing building.

3. Fundamentals of vibration isolation

In a vibration isolation system, the mass controls the amplitudes of the excited system while the isolation performance is determined by the system natural frequency. The latter results from the co-ordination of the amount of mass and the elasticity of the mounts resulting in the static deflection of the mass-spring-system (MSS). Regarding a harmonic excitation, the relationship of the excitation frequency to the system natural frequency (= tuning factor η, see Fig.2) determines the value of the transmissibility factor V_F. In the proximity of resonance (η = 1), damping is an important issue.

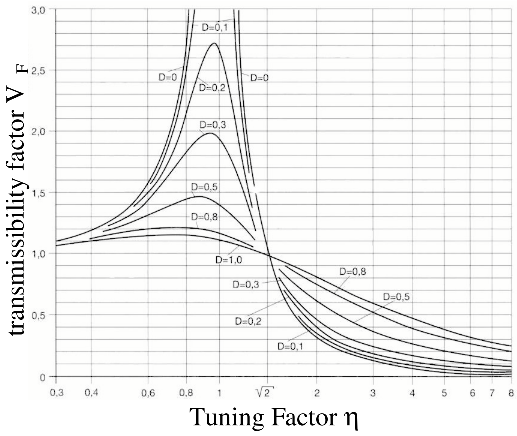

Fig. 2 Transmissibility curves

$$V_F = \left| \frac{1}{1-\eta^2} \right| \quad \text{(undamped)}$$

$$V_F = \sqrt{\frac{1+4D^2\eta^2}{(1-\eta^2)^2+4D^2\eta^2}} \quad \text{(damped)}$$

4. Coil steel springs

The application of coil steel springs is, without doubt, a most efficient way to reduce vibration transmission. The high elasticity is the main feature making system natural frequencies as low as 2 to 8 Hz possible. This is a basic requirement to obtain high mitigation levels not only at high but also at low frequencies of excitation. In addition, low material damping contributes to the excellent performance. Further features of coil steel springs are

- high load capacity
- linear load-deflection curve
- high horizontal stiffness
- equivalent static and dynamic stiffness
- constant elastic properties
- high durability

Coil steel springs are designed to international standards, e.g. to DIN EN 13906-1. They are manufactured to rigorous quality assurance systems to meet all requirements in terms of safety and reliability. Due to the above characteristics they are an ideal tool to reduce the transmission of vibration.

5. Vibration control of trackbeds

Vibration attenuation at the vibration source, i.e. at the rail track, usually represents the preferred solution. It ensures that all buildings located along the track are protected from disturbing vibration.

5.1 General elastic devices

Several provisions are available to deal with the dynamic requirements of a rail track (Fig.3). Rail pads or baseplate pads are mainly arranged to provide some elasticity to the rail track as especially required in the case of a concrete slab track. They have a certain influence on the noise radiated from the rails and contribute to passenger comfort. Sleeper pads improve the contact to the ballast. Other systems like embedded rails or ballast mats can be expected to be more efficient especially with regard to excitation frequencies beyond 40 to 60 Hz.

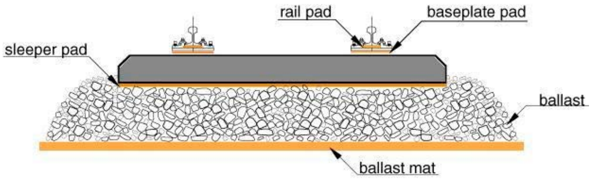

Fig. 3 Elastic provisions at a rail track

5.2 Floating slab track systems

Floating slabs represent the most efficient vibration control measure achieving insertion loss levels of 15 to 25 dB(A) and even more. The elastically supported concrete slabs form dynamically active masses which are isolated from the sub-structure by mounts of rubber or other elastomeric material or, for highest performance requirements, of soft coil steel springs.

While floating slab systems based on elastomeric mounts have been used for trackbed isolation for several decades, the application of coil springs to this technique is comparatively new. In 1994 the first mass-spring-system with coil springs was commissioned in Berlin/Germany. Here, foundations of a hospital were unintentionally linked to a new metro tunnel by concrete injections intended to fill a void in the ground. In order to avoid the expected bridging of vibration a MSS was looked for providing attenuation levels as high as possible. Proposed by the technical university in Berlin, spring elements containing a couple of coil steel springs were arranged between the tunnel invert and the trackbed consisting of prefabricated ballast troughs. The system natural frequency was designed to 7.5 Hz. However, as with many conventional MSS, this technique leaves the elastic mounts not accessible without removing the whole trackbed.

Fig.4 Prefabricated concrete troughs being mounted on steel spring elements

5.2.1 The GSI-System

Accordingly, a new system was developed providing access to the elements from top. In this connection a new track slab concept was developed featuring flat and long in-situ concrete slabs. The benefits in construction are obvious. By using long slabs the number of expensive and often problematic joints can be reduced significantly.

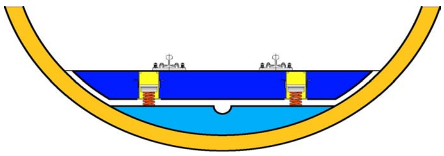

Fig. 5 Principle of a floating slab in a tunnel

The GSI-elements allow the installation of the springs after completion of the slabs. At the same time the slabs which are built directly on top of the sub-structure thus avoiding the bottom formwork are jacked-up and adjusted by means of the springs. Besides the simple operation of handling a jacking tool (Fig. 8), this procedure requires only one technician and a helper. In order to accelerate the installation works two or more of such working units can be established.

Fig.6 Housings placed on a bond-breaking layer

The dynamic behaviour of long track slabs is characterized by their relevant structural natural frequencies which are extremely low and dominated by the coupled system natural frequency determined by the elasticity of the spring elements. This is contrary to short slabs having their relevant structural natural frequencies beyond the usual excitation frequency range of 60 to 80 Hz.

Fig.7 Slab ready for lifting

Fig.8 Spring installation tool

5.2.2 The KY-System

If lateral access to the slabs is given, spring elements can be inserted into recesses arranged laterally in the slabs (Fig. 9). Prior to this the slab must be jacked-up by means of a hydraulic jacking system using the same recesses for placing the jacks.

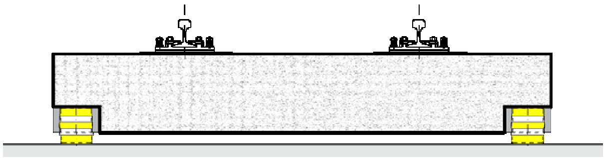

Fig.9 KY-System

These elements may contain a couple of springs thus providing a higher load capacity and allowing a wider and cost-saving spacing of the elements in the longitudinal direction.

Fig.10 KY-spring element

Fig.11 Floating slabs completed

5.2.3 The GP-System

Highly-efficient vibration control measures can also be used on bridge-type slabs or girders with high concentrated support loads (Fig. 12). The GP-System consists of a variety of spring elements designed to high loads. They replace the conventional bridge bearings. For longer structures the GP-elements are equipped with sliding bearings.

Fig.12 Box-type railway bridge girders supported on GP-elements

Fig.13 GP-elements and seismic damper

5.3 Efficiency

The efficiency of a floating slab system depends on several factors. Besides the system natural frequency, there are the slab modes as well as the system damping and the impedance of the sub-structure which also exert a certain influence. The actual efficiency of a floating slab system is defined by the insertion loss which is the difference of vibration levels taken at a reference point beside the slab with and without the isolation system. It goes without saying that in practice, such measurements usually are not possible.

Therefore measurements performed in order to prove the attenuation efficiency of a floating slab track system usually must be limited to the proof of the transmission loss gained between the track slab and a location beside the slab, for instance at the tunnel wall. When high losses prove significant reductions of vibration levels , there is every reason to believe that the remaining vibration level, by assuming a further reduction in the ground, will not be able to cause any problem in the surroundings. However, the measurement of the received vibration levels, e.g. in a residential building, is more reasonable. The results can directly be compared with the limits laid down in a standard (e.g. DIN 4150) or guideline.

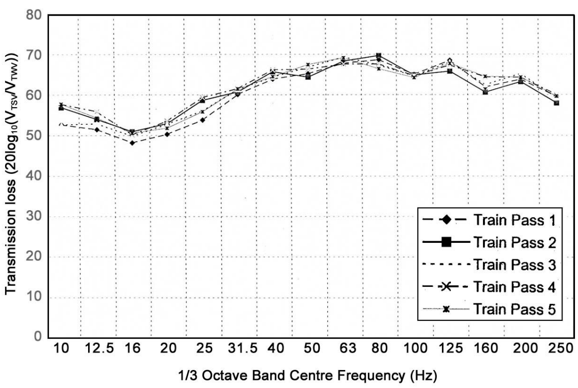

Fig.14 Typical vibration attenuation from track slab to tunnel wall

Fig.14 shows transmission loss curves referring to several trains of the Dockland Light Rail in London passing a GERB steel spring MSS in a tunnel. Regarding low-frequency (mechanical) vibration insertion loss values of 15 to 25 dB(A) can be expected by all types of floating slab systems using coil steel springs.

6. Vibration control of buildings

As for trackbed isolation, coil steel springs are also successfully used for building isolation. This variant has proved to be equally highly efficient and can be applied to almost all types of buildings, tall towers excluded.

In Berlin/Germany, twenty years ago, the first ever building on steel springs was planned to be built on top of a subway tunnel. As there was no experience yet regarding the dynamic behaviour of a building supported on soft steel springs, a comparatively stiff and expensive 7 Hz bearing system was installed at first. Then, after a positive performance of the 5-floor residential building was proved by measurements including those taken under severe wind conditions, the bearing system was tuned down to 4 Hz. This was achieved by reducing the number of supporting springs. Further measurements have shown equally satisfying results. This has encouraged the move towards a 3 Hz system for the next building, a multi-storey office block located in Munich/Germany near to a forge shop.

By that time a great deal of experience was available with the isolation of machinery, including large turbines with long shafts sensitive to disalignment. The benefits of prestressable spring elements developed for turbines could also be used for buildings to control the spring deflections under the completed building. However, buildings with a clear and simple shape which enable to calculate the bearing loads with high accuracy were supported initially on non-prestressable spring elements.

6.1 Prestressable and non-prestressable elements

Prestressable spring elements of GERB manufacture (Fig. 15) consist of two stiff housings with the coil springs sandwiched. Prior to installation the springs are pre-compressed and fixed to that position by heavy-duty prestressing bolts. When placed in position on site, the elements are used like rigid bearings without showing further deflections caused to the increasing loads. Finally, when the building is almost completed, the bolts open automatically.

Fig.15 Prestressable spring element

The spring deflections can be subsequently adjusted as required thus insuring the proper function even if the actual loads do not fully comply with the design loads. If necessary, the elements can be shifted, removed or replaced. This type of element is always recommended when the building loads cannot clearly be calculated due to a complex building shape or when the future use is, as yet, unknown. In order to make use of these options the elements must be accessible. This has to be allowed for at planning stage.

Non-prestressable spring elements (Fig. 16) provide the same static and dynamic options. However, once they are installed and loaded, no subsequent corrections are possible. Therefore no access is required thus reducing demand for space. The contractor must be aware of the progressive spring deflection during construction.

Fig.16 Non-prestressable spring element

6.2 Building on prestressable spring elements

In 1999, the British Film Institute opened an IMAX cinema in the central London borough of Southbank comprising of the largest screen in the UK. This project, situated in the centre of a noisy roundabout and in the close vicinity of Waterloo Station, was quite a challenge for the acoustic consultant (Fig. 18). One of the main problems was the vibration and noise generated by several subway lines located only a few meters below the new building.

Fig.17 Spring elements on columns

Measurements revealed high vibration levels making a high-performance attenuation bearing system necessary. It was decided to install a low-frequency coil spring system.

In co-operation with the acoustic consultant and the design team a 3.5 Hz bearing system was developed consisting of prestressable spring elements placed on three circles of columns supporting the building. (Fig. 17). Enlarged column heads made of steel were designed to take the elements required. With this arrangement of the elastic bearings only the cinema itself was cost-savingly isolated but not the entrance hall and the cafeteria both located between the columns.

Fig.18 Construction site in a roundabout centre

During the entire period of construction the system was monitored by the experts. Measurements were performed at several stages eventually proving the success of the measure. When the project was completed attenuation levels at about 25 dB were confirmed.

6.3 Building on non-prestressable spring elements

In 1994, a 5-floor office building was completed in Berlin/Germany located directly above two subway tunnels crossing the building site diagonally. The tunnel head was only one meter below ground.

Measurements in the adjacent buildings showed vibration levels which indicated the anticipated vibration level inside the future building as exceeding acceptance level up by to ten times. This made a decision for a high-performance steel spring bearing system easy.

Fig.19 Non-prestressable spring elements installed

The constructional requirements were extremely difficult as there were only three old brick foundation clusters available adjacent to the tunnels to support the building. After the preparation of the still strong foundations, non-prestressable steel spring elements were arranged on top of a well adjusted concrete layer (Fig. 19). The decision for this cheaper type of elements was made due to lack of access to the springs once the building was completed. Subsequent adjustments of spring deflections as possible with prestressable elements would have required access to the elements.

Fig. 20 shows the further construction sequence. After steel plates were arranged on top of the springs a stiffening and height adjusting concrete layer was added. Prefabricated slabs served as formwork for the construction of a strong concrete slab bridging the tunnels with an acoustic air gap in between. This slab carries the entire building.

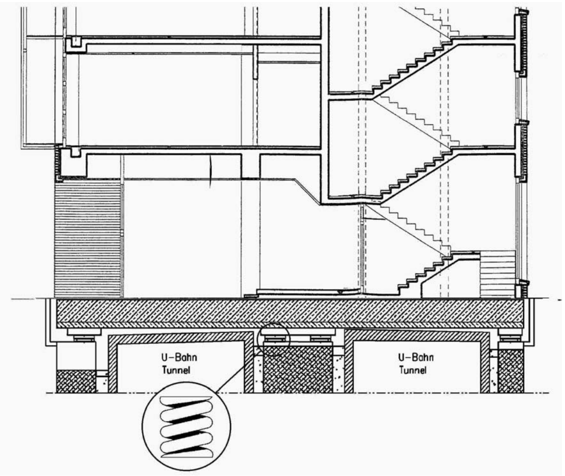

Fig. 20 Construction Details

Measurements performed at several stages of the building construction clearly illustrated the decreasing natural frequency of the dynamic system parallel to the increasing spring deflections. At the end a 3.5 Hz system could be proved.

7. Conclusion

The paper illustrates two options to attenuate vibration and structure-borne noise in buildings generated by trains passing by by means of highly-effective steel coil springs. The springs can be arranged either under the rail track or under the buildings. Both measures are equally good. In both cases different techniques with different spring arrangements are available making tailored solutions possible for almost all requirements. The comparatively soft coil springs allow very low system natural frequencies resulting in high attenuation values even at low excitation frequency levels. They are most efficient, durable, and have high load capacities. The reliability of both options has been proved by long-term and worldwide experience.

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