Dynamic Interaction Between Bridge and Vehicle

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An interactive behavior between a bridge and a vehicle periodically stimulated by road roughness was observed through systematic testing. Periodic roughness was stimulated by using wooden planks placed at various distances across the road. The vehicles, two 7.5-ton trucks, were run across the bridge with varying loads and at varying speeds. The test bridge was a two-span prestressed concrete pedestrian structure on which many sensors were placed. A complete model was developed on the basis of separate components, including excitation, vehicle, and bridge. These components were linked in the final calculating step. Particular attention was paid to determining the stiffness of the superstructure.

Increasing improvements in construction materials and calculation methods have resulted in an increasing reliability level of structures. Major benefits are material saving and slimmer components, which increase the ratio of live load to dead load and change the dynamic behavior of structures. Therefore, there is a need for adequate dynamic analysis methods. Traditionally, the dynamic part of the load is associated with the static load through a dynamic load factor. The basic theory was developed around the turn of the century for the construction of steel railway bridges.

A bridge live load caused by heavy trucks entails a strong dynamic character conditioned on the vehicle dynamic properties. However, one major source of vibration for vehicles is the surface roughness. Therefore, it is necessary to consider a complex dynamic system composed of three components: surface roughness, vehicle, and bridge.

The objective of this study was to investigate the dynamic behavior of the whole system by undertaking a series of systematic tests. The parameters considered included frequency of excitation, vehicle speed, and vehicle mass.

SURFACE ROUGHNESS

The vehicle may undergo vibrations as a result of outside effects. Surface roughness of the road is an important source of vibration that directly influences the vehicle through tire contact. It is important to determine and quantify related parameters.

To describe roughness, the power spectral density function is used. In general, the amplitude decreases as the wavelength increases. The relationship between the vibration frequency of the vehicle body and axles, vehicle speed, and the wavelength of the road roughness is indicated in Figure 1.

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DESCRIPTION OF VEHICLE

The bridge load caused by heavy vehicles can be divided into two categories: static and dynamic. The static part of the load is constant, but it has a variable position. The dynamic part of the load maintains the same position but is time dependent. It is defined by the dimensionless dynamic load increment. Its size depends on the natural frequency of the bridge and the vehicle, the surface roughness, the speed, and other outside effects.

The three major components of the system (surface, vehicle, bridge) determine the dynamic properties of the vehicle-bridge system. Not only the maximum amplitude of the load increment but especially its distribution over the frequency spectrum is important. Different types of vehicles, body and axle masses, and springs and dampers have a considerable influence on the dynamic properties.

DESCRIPTION OF BRIDGE

Tests were carried out on a research bridge in Berlin. Its design characteristics and static behavior are important factors for the evaluation of the dynamic experiments and developement of a calculation model. Other parameters considered include geometry, cross-section values, reinforcement, material properties, and especially the response of the bridge under a static test load. As a result of the test load, cracks occurred in the superstructure, which caused a change in its stiffness; this had to be included when developing the model.

The research bridge is an asymmetric, two-span concrete pedestrian structure with partial prestressing without bond. The spans are 27.6 and 23 m, and the superstructure consists of a double T-girder with a depth of 1.1 m and a width of 4.8 m. The prestressing reinforcement material is made of a high-strength composite (fiberglass) with seven tendons.

A total of 360 sensors were placed on the superstructure to measure the strain in concrete, stirrups, longitudinal reinforcement at the bottom and top of the girder, as well as the concrete and air temperatures. In addition, the forces in the tendons and the bearings could be measured.

For the dynamic tests, the results of the deflection measurement, cracks documentation, and strain of the reinforcement during a former static test load had to be considered because together they determine the actual stiffness. This value was needed for the developement of the model and provided important information for the selection of the points of measurement.

DYNAMIC INVESTIGATIONS

The dynamic tests were carried out to clarify what the influence of the surface-related excitations has on the vehicle and bridge systems

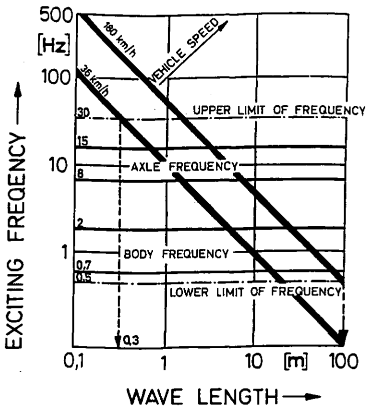

FIGURE 1 Relationship between exciting frequency and wavelength of roughness.

and on their interaction to specify the resulting bridge load. Periodic and impact excitations were chosen.

For the periodic excitations, a quasi-stationary mode was selected. This mode allowed for a parallel form of vibration in both systems, which is particularly important for the analysis of frequency and resonance effects. The impact excitation was used to investigate the influence of the speed. For vehicles, the body mass was changed in three steps and the speed was varied.

The sensors used on the bridge included four measurement bearings, eight strain gauges, and four measuring cylinders for the prestressing force. Nine accelerometers were installed on the superstructure as well.

Two different 7.5-ton test trucks with 200-l water containers for ballast were used for the dynamic tests. Each vehicle was equipped with four accelerometers, which were placed on the front and rear axles and on the front and rear areas of the body to be able to distinguish the different kinds of movements in the vibration modes. The vehicle and the measuring device were connected by a cable that allowed for a simultaneous recording of the bridge and vehicle signals.

Planks 5 cm thick and 25 cm wide were positioned in such a way that the front and rear axles went over the planks at the same time. This led to a harmonious up-and-down movement of the vehicle. Exciting frequencies between 0.5 and 8 Hz were observed. The vehicles were driven at speeds between 10 and 40 km/hr.

Evaluation in Time Domain

Evaluation in the time domain provides the basis for determining the dynamic increments and the exact exciting frequencies. The predetermined parameters include the average speed between the two end points of the bridge, the exact speed over the planks, the static part of the measured amplitude, the extreme amplitudes of the dynamic part, the corresponding frequency when counting the peaks, and the exciting frequency of the vehicle.

The frequencies counted from the time curves provided necessary additional information about the frequency spectra. Because of the variable location of the vehicle mass, the natural frequencies of the coupled system changed. Within the frequency spectrum, the effects appeared to be nonlinear and, therefore, no definite interpretation was possible. Only after consideration of the results in the time and frequency domains did all of the information become available. The first three natural frequencies of the bridge are 2.4, 4.5, and 9.6 Hz.

First, the amplitudes of the dynamic part were evaluated while taking into account the frequency for the periodic excitation. To make the resonance effect clear, even the test runs with various loads were put together in one diagram per point of measurement (Figure 2) to determine the reaction of the bridge. It is clear that the amplitudes in the area of 1.5 to 3.5 Hz are significantly higher than those at other frequencies. This shows that there is a resonance between the vehicle and the bridge.

The measured amplitudes did not indicate, however, the differences in the individual load levels, as expected. The largest value was even measured for the empty vehicle. One explanation may be that the laminated spring could not take advantage of the friction effect that resulted from a sufficiently loaded vehicle. In this case, the friction between the segments of the spring was so strong that the spring effect was reduced. This led to a higher axle impact and therefore to larger dynamic amplitudes.

Evaluation of Dynamic Increments

Figure 3 (*left*) indicates for the vehicle periodically in vibration the relationship between the dynamic increments in the reinforcement and the exciting frequency. In the other diagram in Figure 3 (*right*), the relationship between these increments and the speed for the vehicle excited by a plank 2 m wide and 5 cm high for impact excitation is shown. The dynamic increments increase as the load of the vehicle decreases. During the periodic vibration, these differences appear clearly at frequencies at which resonance occurs, between 1.5 and 3.5 Hz.

During the test runs with the fully loaded vehicle, the dynamic increment increased from 75 to 150 percent in the resonance field. These observations were also confirmed when using the plank. However, resonance effects at certain speeds were not found. The dynamic increment increases at an almost steady rate as the speed increases.

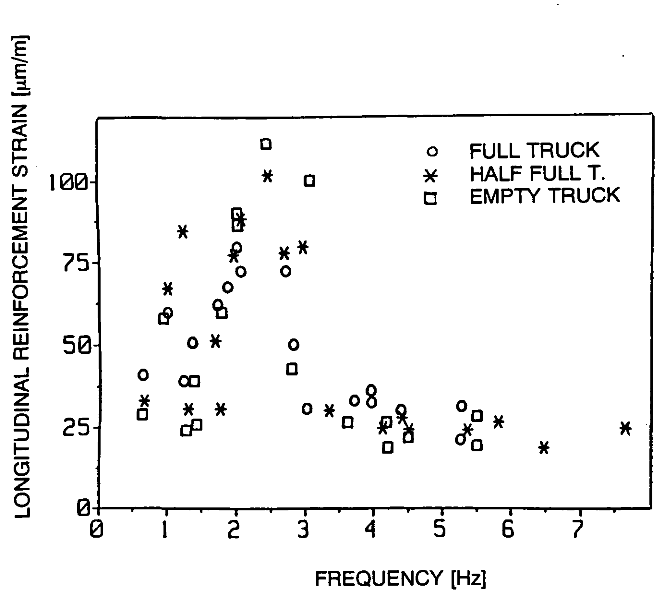

FIGURE 2 Dynamic amplitude for periodic excitation.

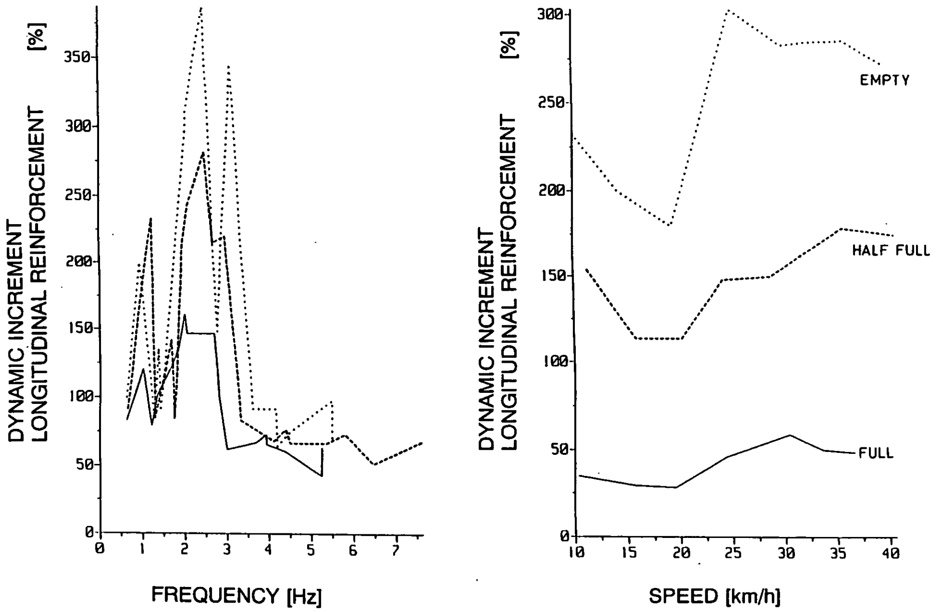

FIGURE 3 Dynamic increments.

Frequency Spectra of Bridge

For the evaluation in the frequency domain the data were transformed using Fast Fourier Transformation. Figure 4 demonstrates that the peaks of the frequency spectra for the runs with periodic vibration are always particularly high when the response and the stimulating frequencies are in tune, as in the case of resonance. Frequencies between 1.5 and 3.5 Hz are especially easily obtained.

In Figure 4*a*, all the values on the graph were in the resonance area or on one of the lines having stimulating frequency/response frequency rates between 0.5 and 3 Hz. In the three-dimensional graphs, the highest amplitudes are found in the resonance field, whereas the smaller amplitudes correspond with the higher frequency rates. Stimulating frequencies of more than 3 Hz, even in the resonance field, lead to small peaks. These observations imply the existence of a resonance rectangle that is limited by stimulating frequencies of up to 3 Hz and by response frequencies between 1.5 and 3 Hz.

Frequency Spectra for Vehicle

The three-dimensional view of the vehicle's reactions (Figure 5) is presented in the same way as the overview of the bridge. The axles are easily excited over all the frequency areas and respond with frequencies between 2 and 15 Hz. The body shows a concentration in the lower frequency range at stimulating frequencies under 2 Hz and response frequencies of up to 5 Hz. However, the truck body vibrates less when the stimulating frequencies go up to 6 Hz and the response frequencies reach 12 Hz. The top view shows the vibrations of the body to be between 1 and 5 Hz and those of the axles to be between 9 and 14 Hz.

For a fully loaded vehicle, there is a noticeable concentration within the resonance rectangle with a 2-Hz stimulating frequncy and a 2.5-Hz response frequency. However, the resonance field for

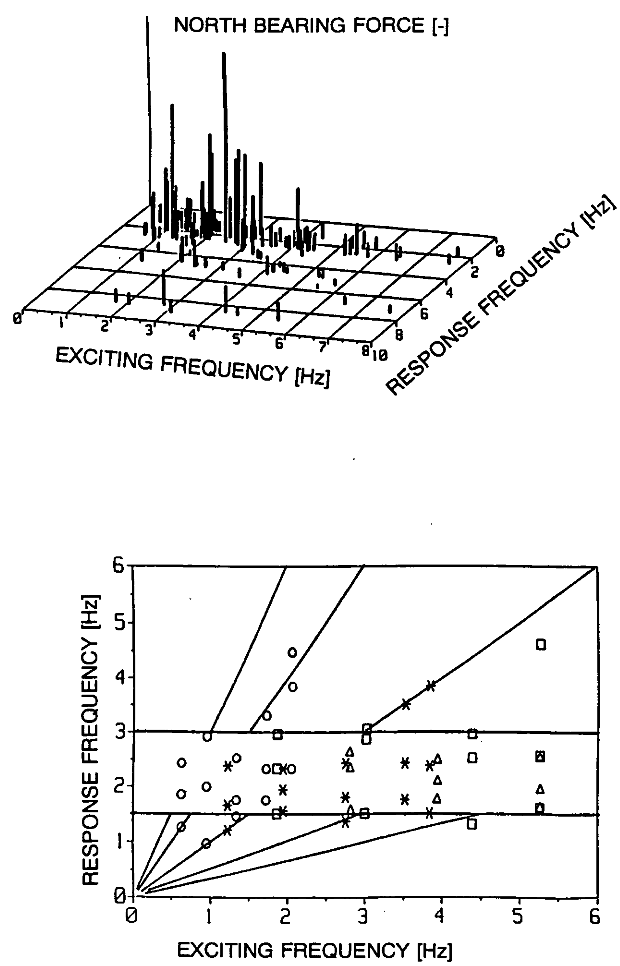

FIGURE 4 Spectral behavior of bridge.

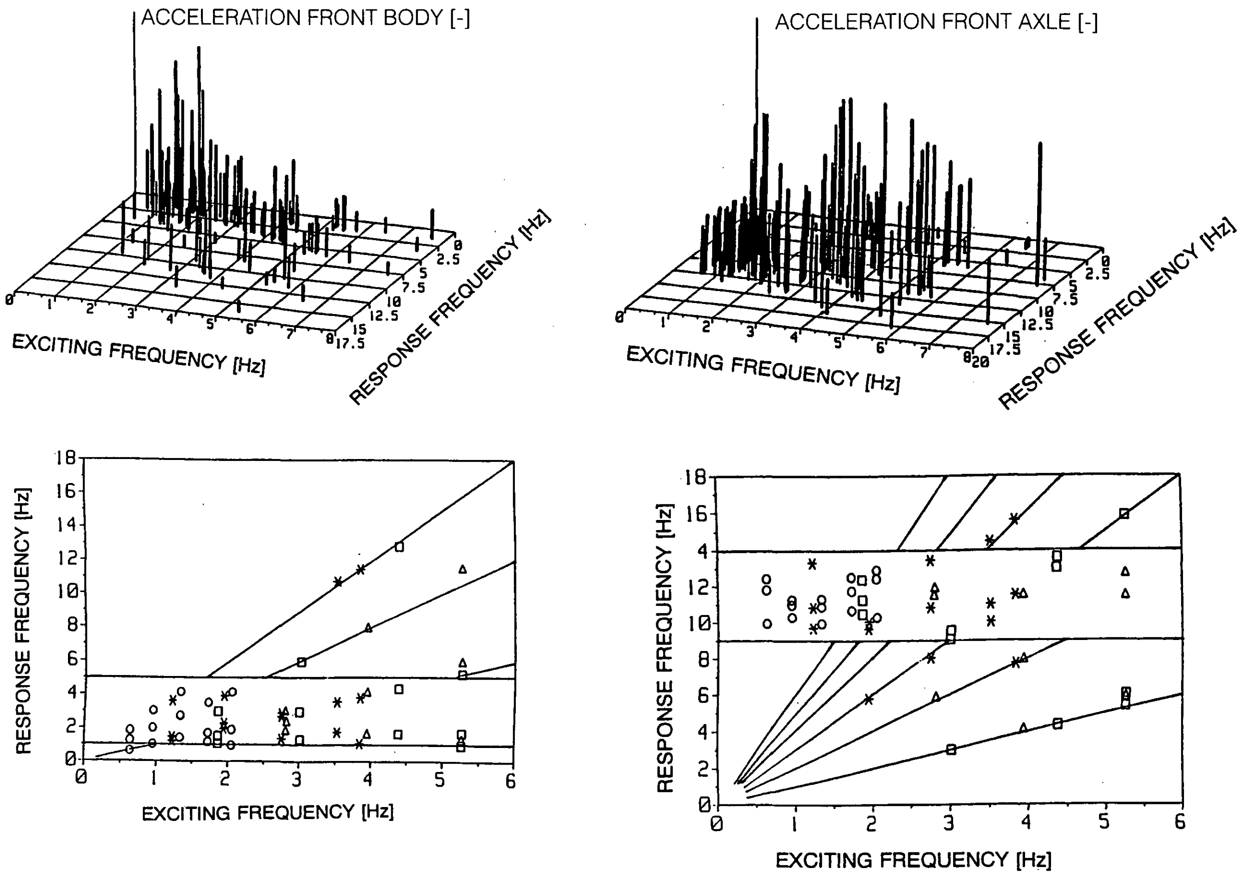

FIGURE 5 Spectral behavior of vehicle.

a less loaded vehicle is not as easily identifiable. The empty vehicle responds with considerable amplitudes of up to 10 Hz. This behavior cannot be explained by the presence of a higher natural frequency of the body. The cause is probably to be found in the nonlinear behavior of the vehicle's springs.

Cross-Power Spectra

To consider the interaction between the vehicle and the bridge, the cross-power densities between the signals of the vehicle and the bridge were calculated. This means that the frequencies that appear in both spectra were amplified, whereas the others were almost nonexistent. The cross-power spectra (CPS) were calculated between the bridge signals on one side and the axles and the body signals on the other.

The three-dimensional view in Figure 6 shows the clear differences between the axles and the body CPS. The axle CPS cause interactive responses with high peaks of up to 12 Hz. Noteworthy peaks of only up to 2.5 Hz appeared in the body CPS. Observation of the stimulating frequencies shows that the body CPS can be amplified only up to 3 Hz, whereas the differences between the lower and the higher stimulating frequencies are less clearly distinct at the axle CPS. A resonance field manifests itself clearly for the body CPS and is limited by stimulating frequencies of 3 Hz and response frequencies of 2.5 Hz.

In the top view, plotted points were most often found on the lines showing the proportional rates of 1, 2, and 3 for the axle crosses and on those of 1, 0.5, and 2 for the body crosses. It was observed that 83 percent of the peaks are located within a 10 percent range from the proportionality lines, with 40 percent of the values located within 10 percent of the resonance Line 1. This proves that the load on bridges is frequency dependent.

Development of Analytical Model

By using the knowledge obtained from the static and dynamic investigations it became possible to model the interactive relationship for other parameters by using a finite elements program with frame elements. Particular emphasis was placed on the adaptability to various forms of stimulation and different types of vehicles and bridges. It was necessary to consider and optimize separately each component of the dynamic system.

The model includes the forces resulting from the mass, dampers, and springs of the vehicle and bridge systems. The stimulating function is locally fixed and was calculated by combining the surface roughness of the test road with the speed.

The direct calculation of the system under a moving dynamic load can, if necessary, be approximated by using dynamic influence lines. Their calculation is similar to the determination of the static influence lines by replacing the moving static load by a vibrating

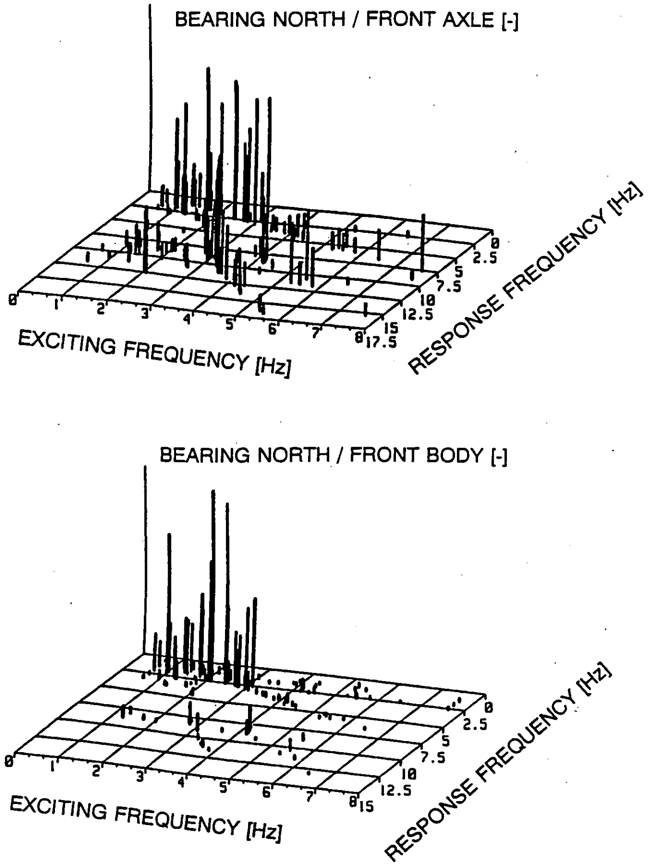

FIGURE 6 Spectral behavior of interaction.

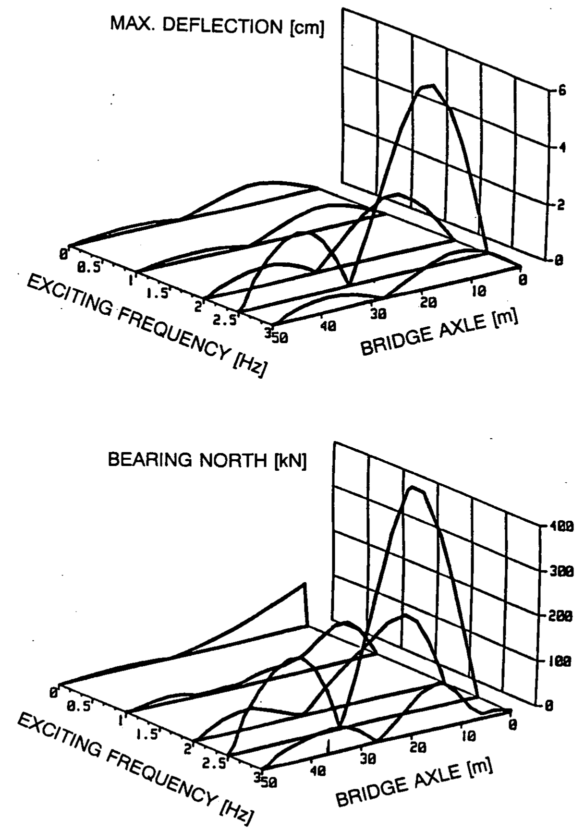

FIGURE 7 Dynamic influence lines.

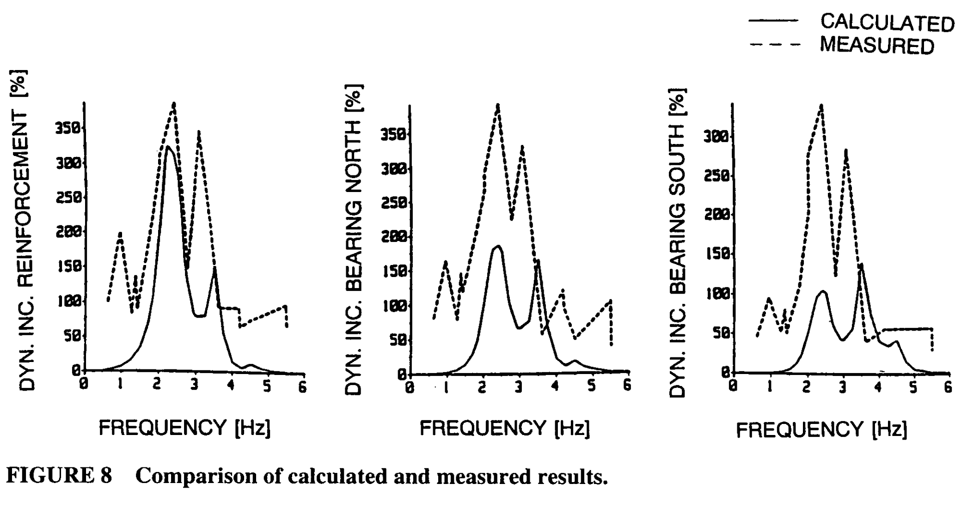

FIGURE 8 Comparison of calculated and measured results.

force whose effect on the system can be evaluated at any point. In Figure 7, a static and four dynamic influence lines are shown at various stimulating frequencies for a standard load of 100 kN. The deflections, bending moments in the middle of the long field, and the forces of the supporting points are also shown. The dynamic influence lines are primarily differentiated according to the size of their amplitudes, depending on their closeness to the stimulating frequency and the natural frequency of the bridge. Their construction, however, is different from that of the static influence lines, whose amplitudes are located at a stimulating frequency of 0 Hz.

For each vehicle load, a specific calculation for each frequency is necessary. To simulate a test run on a computer, a variable connection between the vehicle and the bridge is necessary. The whole system responds to the movement of the truck by changing its natural frequencies. A direct comparison of frequencies and amplitudes obtained by analysis and tests is shown in Figure 8. Although the calculated values were slightly above those measured for the fully loaded vehicle, for the half-loaded vehicle it was the other way around. For the empty vehicle, the amplitudes measured at least for both supporting points were clearly above those calculated. Outside the resonance fields, a basic value for the dynamic increments remained that fundamentally did not appear in the theoretical model. In general, the measured and the calculated values were satisfactorily similar.

In the frequency domain, a good conformity could be observed as well. The global structure of the main masses of the vehicle and the bridge emerged for both values. The developed model can be used for the analysis of the effect of variable road surface, various types of bridges, and for special types of vehicles carrying variable loads.

SUMMARY AND CONCLUSIONS

An interactive behavior between a bridge and a vehicle periodically stimulated by road roughness was observed through systematic testing. The evaluation of the bridge's reactions showed a clear increase in the response amplitudes at stimulating frequencies between 1.5 and 3 Hz and at response frequencies that were multiples of the excitation frequency. Thus, resonance fields are important in the bridge spectral behavior. Their limits are a stimulating frequency of up to 3 Hz and a response frequency between 1.5 and 3 Hz.

The vehicle frequency behavior was found to be similar to that of the bridge. The resonance fields are limited differently because of the presence of the axle frequencies. However, the obvious influence of the natural frequencies of the individual elements remains.

To investigate the interaction, the CPS between the bridge and vehicle signals were calculated as a function of the stimulating frequencies. Resonance fields whose limits were dependent on the natural frequencies of the systems involved were also observed.

It is clear that the load magnitude depends on the parameters related to the vehicle and bridge frequencies. They include primarily the natural frequencies of the components of the dynamic system. The stimulating frequency is the most significant effect that results from the road roughness and the speed.

For the design of bridges subjected to dynamic loads, the classical dynamic load factor does not affect the natural frequency behavior of the bridge, vehicles, speed, and road roughness. For the design of dynamically sensitive bridges, further dynamic calculations are necessary.

For the maintenance of existing bridges, it can be concluded that more attention should be paid to the level of the road roughness at the approach and on the bridge. The surface roughness is the major cause of the dynamically related damages to the bridge. It is suggested that a catalog of limit values for various types of surfaces be established and become a part of the design and construction code.

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