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EXCITATION METHODS FOR BRIDGE STRUCTURES

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ABSTRACT.
This paper summarizes the various methods that have been used to excited bridge structures during dynamic testing. The excitation methods fall into the general categories of ambient excitation methods and measured-input excitation methods. During ambient excitation the input to the bridge is not directly measured. In contrast, as the category label implies, measured-input excitations are usually applied at a single location where the force input to the structure can be monitored. Issues associated with using these various types of measurements are discussed along with a general description of the various excitation methods.

1. INTRODUCTION.

Dynamic testing of bridges has become more prevalent in recent years as is evident by the increasing number of tests on bridges reported at the recent IMAC Conferences. These tests are performed for a variety of reasons including studies of the aerodynamic response of bridges, correlation of numerical models with measured data, seismic assessment of the bridges, bridge condition monitoring, and studies related to the development of dynamic impact factors for design of the bridges. In the course of these studies many different types of excitation methods have been applied to bridge structures.

Recently, a review of dynamic bridge testing literature has been performed at Los Alamos National Laboratory[1]. This paper will summarize the finding of this review with regards to the excitation methods that have been used in numerous bridge tests. Although considerable effort has been made to make this a thorough review, the authors realize that the data bases searched do not give complete coverage to literature published outside the United States, particularly conference proceedings. Only papers in english have been reviewed. Also, it is sometime difficult to obtain testing reports prepared for local highway departments, hence, such reports have not, in general, been included in this summary although many of the reviewed papers cite such reports. It is the intent of this paper to extend the material in a previous paper presented by Green[2] at IMAC XIV on a similar subject.

The methods of exciting a bridge for dynamic testing fall into two general categories: 1.) Measured-input tests; and 2.) Ambient tests. In general, tests with measure inputs are conducted on smaller bridges. For larger truss, suspension and cable-stayed bridges, ambient tests become the only practical means of exciting the structure.

For a particular excitation method, length limitations preclude listing all papers that discuss the method. Therefore, this review has adopted the practice of mentioning the earlier references to a particular method. The reader is referred to the web site http://esaea-www.esa.lanl.gov/damage_id where Reference 1 will appear. This document will have a more complete listing of references related to particular excitation methods.

2. OTHER SUMMARIES

An early summary of dynamic testing of highway bridges in the U.S. performed between 1948 and 1965 was presented by Varney and Galambos (1966)[3]. Iwasaki, et al. (1972)[4] summarized tests performed in Japan between 1958 and 1969 to determine the dynamic properties of bridge structures. Another summary of field and laboratory tests on bridge systems was presented by Ganga Rao (1977)[5]. Cantieni (1984)[6] summarized dynamic load testing of 226 beam and slab-type highway bridges conducted in Switzerland between 1958 and 1981. Cantieni pointed out that dynamic testing of highway bridges was required in Switzerland between 1892 and 1913. Salawu and Williams (1995)[7] provide a review of full-scale dynamic testing of bridges where methods of excitation are examined and reasons for performing dynamic tests are summarized.

Bakht and Pinjarkar (1989)[8] presented a review of literature dealing with bridge dynamics in general and dynamic testing of highway bridges in particular, giving special attention to impact factors, their various definitions, and factors that influence these parameters.

The extensive use of testing in the evaluation of bridges has resulted in the American Society of Civil Engineers' (ASCE) Committee on Bridge Safety publishing a guide for field testing of bridges in 1980[9]. This guide includes an extensive reference list of papers summarizing previous bridge tests. Also discussed are static and dynamic load application methods, instrumentation, data acquisition, and methods for measuring *in situ* material characteristics. A RILEM committee 20-TBS (1983)[10] proposed a standard for *in situ* testing of bridges. This standard addressed both static and dynamic testing of bridges. Topics that are summarized include categories of load tests, test preparation, test procedures, evaluation of load steps, evaluation of load tests and reporting of results.

3. AMBIENT INPUTS

Ambient excitation is defined as the excitation experienced by a structure under its normal operating conditions. All bridges are subjected to ambient excitation from sources such as traffic, wind, wave motion, and seismic excitation. This type of excitation has been used during dynamic testing of both large and small bridge structures. Typically, the input is not, or can not be, measured during dynamic tests that utilize ambient excitation. For larger bridges ambient excitation is the only practical means of exciting the structure as the ability to input significant energy into structure, particularly at higher frequencies, by some mechanical device becomes more impractical as the size of the structure increases. Ambient excitation is also used with smaller bridges when other constraints prevent the bridge from being taken out of service during the tests. The use of ambient vibration often provides a means of evaluating the response of the structure to the actual vibration environment of interest. A drawback of using ambient excitation is that this type of input is often non-stationary. Also, because the input is not measured it is not known if this excitation source provides input at the frequencies of interest or how uniform the input is over a particular frequency range. Even when measured-input excitations are used, ambient vibration sources are often still present producing undesirable and often unavoidable extraneous inputs to the structure. The varieties of ambient excitation methods that have been reported in the technical literature are described below.

3.1 AMBIENT: TEST VEHICLES

One of the first ambient vibration studies of bridges is reported Biggs and Suer (1956)[11]. The authors point out that up to this point in time vibration of bridges has been ignored in their design. They point out a difficulty associated with using a test vehicle that has been noted in numerous subsequent studies: that frequencies observed while the test vehicle was on the bridge are not necessarily those of the bridge, but are related to the natural frequency of the vehicle suspension system. Also, these authors noted that the natural frequencies could vary as much as 20% when traffic is on the bridge.

Van Nunen and Persoon (1982)[12], as a part of a larger study on the vibration of a cable-stayed bridge under wind loads, determined the modal characteristics of the bridge by driving a truck back and forth across its deck. Road surface irregularities were accentuated by placing wooden beams on the deck. These irregularities resulted in a random excitation of the bridge.

Swannell and Miller (1987)[13] performed twenty-one tests on the same bridge structure. A vehicle was driven over the bridge and several different vehicle approaches to the bridge were examined: constant speed, and gentle, sharp, and sudden braking. The vehicle was also driven over a bump at the entrance to the bridge to enhance the input to this structure.

Agarwal and Billings (1990)[14] report tests on a prestressed concrete slab bridge that were conducted because of complaints regarding the excessive vibration and movement of the bridge. Vibration was induced into the bridge by running one or two test vehicles over the bridge in various patterns. The authors make the important observation that bridges having their first flexural resonant frequency in the range of 2.5 – 4.0 Hz have been found to display high dynamic response because these frequencies match the bounce frequency of modern commercial vehicle suspensions.

As part of a study to determine dynamic amplification factors, Proulx, Hebert, and Paultre (1992)[15] performed ambient vibration testing of a steel arch truss bridge using the excitation from a single truck driving at different speeds. Resonant frequencies of the bridge were calculated from peaks in the power spectral density function corresponding to high coherence levels. Peaks corresponding to low coherence are assumed to caused by bridge-vehicle interaction rather than the natural frequencies of the bridge.

Casas (1995)[16] reports the results of ambient vibration tests on several bridges. Ambient excitation was performed with various test vehicles, some of which were driven over standard obstacles.

3.2 AMBIENT: TRAFFIC

For bridges that can not be taken out of service, traffic loading is the primary method for exciting the structure. Many times traffic excitation is coupled with other ambient excitation sources such as wind. With traffic excitation the assumption is often made that the ambient vibration source is a white noise random process. Turner and Pretlove[17] state that this assumption is based on the random arrival times of individual vehicles; the random nature of the vehicles' suspension systems; and the randomly distributed road surface irregularities. Depending on the coupling between torsional and lateral modes, traffic excitation has the limitation that it may not sufficiently excite the lateral modes of a bridge and these modes are often of interest, particularly in seismic studies.

Gates and Smith (1982)[18] summarized the ambient testing procedures applied to 57 highway bridges in California. These authors presented detailed discussions of problems associated with ambient vibration testing. Problems that were identified included: (1) Peaks in the Fourier spectra that result from non-stationary inputs can be interpreted as resonant responses of the structure, and (2) Structural properties can change when acquiring long time windows of data.

Farrar, et al., (1994)[19] report ambient vibration tests on the I-40 Bridge over the Rio Grande prior to a damage detection study. Traffic excitation on the bridge of interest was first used as the ambient vibration source. After traffic had been removed from the bridge, traffic on an adjacent bridge was used as the excitation source.

Brownjohn (1997)[20] performed ambient vibration tests of a footbridge in Singapore using a person walking and jumping on the bridge as the excitation source. The analysis of the bridge's response to the pedestrian inputs showed that the "bouncy" response was caused almost entirely by two modes near 2 Hz (symmetric and asymmetric vertical modes) that coincided with the typical frequency of normal pedestrian footfall.

3.3 AMBIENT: WIND AND WAVES

Carder (1937)[21] documents vibration studies done of the San Francisco-Oakland Bay Bridge and the Golden Gate Bridge. These studies were conducted to determine the probability of damage caused by resonance during seismic excitation. The experimental procedure consisted of measuring ambient vibration data with a photographic seismograph that was attached to the bridge. Wind, moving water, traffic, or people working on the bridges caused the recorded vibrations.

Studies of wind-induced vibration measured on the Golden Gate bridge are summarized by Vincent (1958)[22]. This paper discussed the development of a mechanical accelerometer developed for this bridge and results obtained from measurements made with an array of these accelerometers. The results were used to verify that structural modifications to the bridge would prevent objectionable torsional vibrations.

3.4 AMBIENT: SEISMIC GROUND MOTION

Wilson (1986)[23] reported on the response of a highway bridge to an actual strong motion earthquake, comparing results with finite element analysis. This ambient vibration problem differed from previously cited examples, as the input to the structure was ground motion for which a measurement was obtained. A similar study on the response of a previously instrumented, two-span concrete bridge subjected to a strong motion earthquake was reported by Werner, et al. (1987)[24]. Related studies using the same two-span bridge data were subsequently reported by Levine and Scott (1989)[25] and by Wilson and Tan (1990)[26]. Finally, ambient vibration testing of a suspension bridge anchorage subjected to both seismic motions and micro-tremors was presented by Higashihara, et al. (1987)[27].

4. MEASURED-INPUT EXCITATION

Methods for determining the modal characteristics (resonant frequencies, mode shapes, and modal damping ratios) of structures subjected to measured inputs are well established, particularly when the input forcing function is well characterized. In the measured-input excitation testing of bridges, a wide variety of forcing techniques are used including various type of shakers, step-relaxation, and various methods of measured impact. The methods of measured input excitation that have been applied to bridge structures are summarized below.

4.1. MEASURED-INPUT: IMPACT

Impact excitation has been used during numerous tests of smaller bridge structures. This type of excitation offers the advantage of quick setup time, mobility, and the ability to excite a broad range of frequencies. Precautions must be taken to avoid multiple impacts. In general, impact excitation is not practical for excitation of bridge's lateral modes. Many variations of impact testing have been applied to bridge structures. These variations are summarized in the references sited below.

Askegaard and Mossing (1988)[28] measured resonant frequencies and modal damping in a reinforced concrete footbridge over a three-year period. Impact excitation was applied by dropping weight on a rubber buffer. To study the ability to identify damage from changes in vibration characteristics, Agardh (1991)[29] identified modal properties of two subsequently undamaged and damaged concrete bridges using impact excitations. The impact loads were achieved by dropping weights onto a shock absorber that prevented rebound. Wood, Friswell and Penny (1992)[30] report a bolt gun that has been used to excite bridge structures with an impulsive load. The gun uses an explosive charge to fire a nail into a small striker plate. A mat between the structure and the plate acts as a filtering device. The gun must be withdrawn immediately after firing to avoid multiple impacts. Miller, et al. (1992)[31] performed field tests on a three-span reinforced concrete slab bridge using an impact hammer. Aktan, et al. (1992)[32] reports impact tests performed on a three span highway bridge that were part of a damage detection study. Multiple-reference impacts (loading the structure at more than one point) were used in this study. Agardh (1994)[33] discusses in detail the development of an impact device consisting of a mass, damper and load cell. Tests were then carried out to evaluate the characteristics of this impacting system. Green and Cebon (1994)[34] performed impact tests on a highway bridge to develop parameters that are needed to model the dynamics of bridge-vehicle interaction. Linearity checks were performed by dropping the impact weight from different heights. Pate (1997)[35] conducted forced vibration tests on the Alamosa Canyon Bridge north of Truth or Consequences, NM. Impact testing was conducted by dropping weights onto a shock absorber suspended from the bottom flange of a girder.

4.2. MEASURED-INPUT: STEP– RELAXATION

Step-relaxation inputs typically involves the sudden release of a static force that has been applied to a point of the structure. This method can excite a wide range of frequencies. The most common method of applying the force to a bridge is to use a tensioned cable. An explosive bolt-cutter can then be used to quickly cut the cable. A load cell or strain gage mounted inline or on the cable is used to monitor the force in the cable. Drawbacks of this method include the possibility for additional unmeasured inputs from the free cable striking the structure and the inherent safety issues associated with a tensioned cable. Also, the modes that have a node point at the point where the static force is applied will not contribute to the response.

Marecos, Castanheta and Trigo (1969)[36] provide one of the earlier summaries where step-relaxation excitation methods were applied to a large suspension bridge structure. In one of the first investigations that studied the transverse dynamic behavior of bridges, Douglas (1976)[37] performed step-relaxation tests on a six-span continuous composite girder access-ramp bridge. Ohlsson (1986)[38] performed swept sine and step-relaxation tests on a cable-stayed bridge in Sweden. The authors point out that it is difficult to perform forced vibration tests on such a structure because of environmental excitation sources such as wind. As an alternative to tensioned cables or bars, Richardson and Douglas (1987)[39] investigated the dynamic response of a reinforced concrete highway bridge vertically loaded by hydraulic jacks with quick-release mechanisms. Comparison between ambient excitations and step relaxation tests are presented by Ventura, Felber and Stiemer (1996)[40] and Gentile and Cabrera (1997)[41] where, in gerenal, good agreement was obtained between dynamic properties identified using both excitation methods.

4.3. MEASURED-INPUT: SHAKER

Many measured inputs to bridge structures have been applied with either rotating unbalance, servo-hydraulic or electodynamic shakers. Shakers offer the advantage of being able to vary the input waveform. Typically, harmonic, random or swept-sine signals are generated with a shaker. Electrodynamic shakers have difficulty producing lower frequency excitations and are limited in the force levels that can be generated. Servo-hydraulic shakers can provide higher force levels, but have difficulties producing higher frequency excitations. In practice, eccentric mass shakers have not been used to apply loads in the vertical direction. All types of shakers have a considerable amount of infrastructure that is needed for their operation such as feedback-control hardware and cooling systems. They are not, in general, very portable and are relatively expensive.

Shepherd and Charleson (1971)[42] determined resonant frequencies and damping for a multi-span continuous deck bridge at various stages of bridge construction using an eccentric mass shaker. Kuribayashi and Iwasaki (1973)[43] determined modal characteristics on 30 highway bridges when subjected to transverse harmonic excitation also using an eccentric mass shaker. In addition to step relaxation tests, Ohlsson (1986)[38] performed swept-sine tests on a cable-stayed bridge in Sweden using an eccentric mass shaker. Cantieni and Pietrzko (1993)[44], reported the modal testing of a wooden footbridge using a randomly driven servo-hydraulic shaker. Deger, Cantieni, and Pietrzko (1994)[45] used a similar excitation system to apply burst random inputs to a concrete arch bridge. Salawu (1995)[46] and Salawu and Williams (1995)[7] conducted a forced vibration test on a reinforced concrete bridge with voided slab construction. A hydraulic actuator provided random excitation to the bridge. A detailed description of the hydraulic actuator is given in Salawu and Williams (1994)[47] Miloslav, Vladimir, and Michal (1994a)[48] performed swept-sine vibration tests on a footbridge in Prague, Czech Republic using an electrodynamic shaker. Mayes and Nusser (1994)[49] discuss the development of a 1000-lb peak amplitude shaker for tests performed on the I-40 Bridge over the Rio Grande. One major requirement that had to be taken into consideration was that the shaker could only exert vertical forces on the bridge. The construction of the shaker was affected greatly by this parameter. The shaker also had to be designed to receive sinusoidal and random excitation signals.

Other studies reporting the use of shaker for bridge excitation include Crouse, et al. (1987)[50] Salane and Baldwin (1990)[51]; Deger, er al. (1995)[52]; Shelley, et al. (1995)[53]; Haritos, Khalaf and Chalko (1995)[54]; and Link, Rihrmann and Pietzko (1996)[55].

5. OTHER INPUT METHODS

Tilley (1977)[56] discusses different methods of measuring damping in bridges. Field test methods discussed include excitation methods such as driving a test vehicle over the bridge, step-relaxation, single-pulse loading using small rockets, periodic loading (eccentric mass shakers, people jumping in unison, and pulling on ropes), and ambient excitation.

Pietrzko and Cantieni (1996)[57] report a modal test of a bridge where rocket engines were used to excite the structure. The rocket engine was used to improve the ability to excite the structure below 1 Hz. A servo-hydraulic shaker was used to excite the structure above 1 Hz. Reciprocity checks showed that the structure behaved in a nonlinear manner and was sensitive to the location of the excitation source.

6. SUMMARY

This paper has summarized methods of excitation that have been used in past dynamic testing of bridge structures. The attributes and difficulties associated with the various excitation methods have been discussed in a very general manner. Although there does not appear to be consensus that one particular method is better than another, for large bridges ambient excitation methods are the only practical method of exciting the structure. The reference list does not contain all papers dealing with dynamic testing of bridge structures. The tact taken in presenting the various excitation methods was to list the first papers that mention a particular method and then list subsequent papers that discuss notable variations of that method. The reader is referred to reference 1 for a more detailed summary of dynamic testing of bridges. This report contains a more thorough list of references pertaining to excitation methods and dynamic testing of bridges, in general.

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