FULL-SCALE AMBIENT VIBRATION MEASUREMENTS OF THE GOLDEN GATE SUSPENSION BRIDGE-INSTRUMENTATION AND DATA ACQUISITION

R.L. NIGBOR (I)

SUMMARY

Extensive measurements were made of the wind and traffic-induced vibrations of the mainspan, one sidespan, and one tower of the Golden Gate Bridge. The purpose of these measurements was to experimentally determine modal parameters of the structure. Due to the bridge dimensions and design, field conditions, and the extent of the data required, many unique and challenging problems were present in the design of the instrumentation system and in the logistics of the data acquisition. The field portion of the project is discussed in this paper, and the problems encountered and their solutions are described.

INTRODUCTION

In order to verify the accuracy of mathematical models of a large, complex structure such as the Golden Gate Bridge, measured modal characteristics of the actual structure are required. Ambient vibration measurements have been used to provide these data for a variety of civil structures. Many detailed ambient vibration studies have been performed on buildings and dams, but few have been performed on suspension bridges. Studies by Rainer and Van Selst (Ref. 1) and Abdel-Ghaffar and Housner (Ref. 2) are two of the more detailed of these.

In this investigation, the wind and traffic-induced ambient vibrations of the Golden Gate Bridge were measured by a team from both the Princeton University Civil Engineering Department and Kinemetrics, Inc. Vibrations were measured at 18 stations on the mainspan and sidespan and 10 stations on one of the two towers. Wind speed was also measured concurrently with the vibration data. Analog data were recorded on magnetic tape and were later digitized for computer analysis. The detailed computer analysis was performed at Princeton University by Abdel-Ghaffar, and is discussed in another paper. This paper describes the instrumentation and data acquisition techniques used in the field portion of the project.

DESCRIPTION OF THE BRIDGE

The Golden Gate Bridge lies across the entrance to the San Francisco Bay and joins the Northern and Southern peninsulas. Construction began in 1933, and in 1937 the bridge was opened to traffic. In 1952, additional modifications were made to the lateral bracing system to increase the rigidity of the roadway after a strong windstorm in 1951 caused some structural damage to the bridge.

(I) Kinemetrics, Inc., Pasadena, California, USA

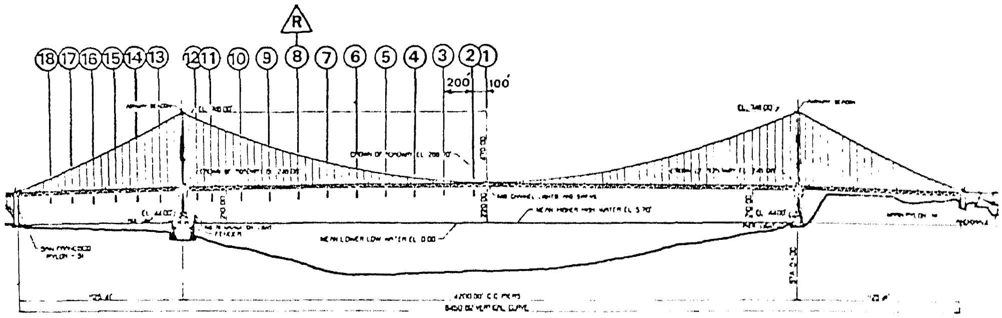

Fig. 1 ELEVATION OF GOLDEN GATE BRIDGE SHOWING SPAN MEASUREMENT LOCATIONS

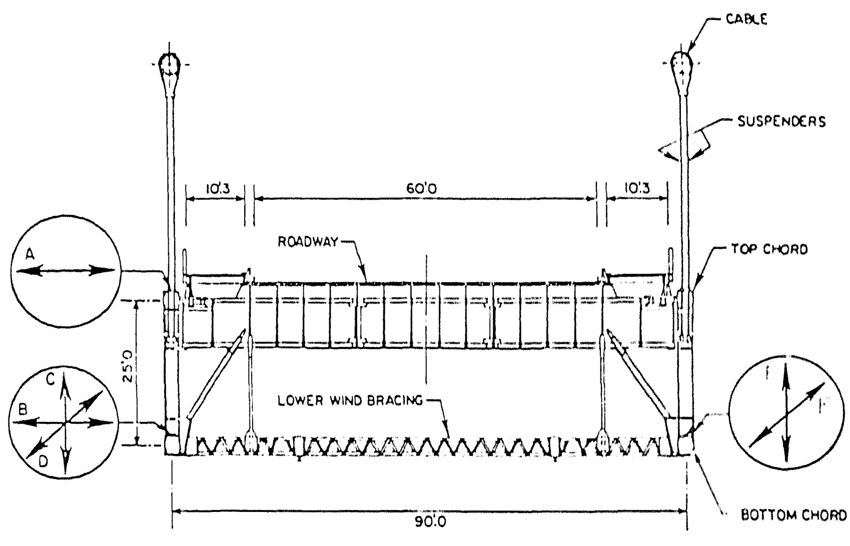

Fig. 2 TYPICAL SPAN CROSS-SECTION SHOWING SENSOR PLACEMENT

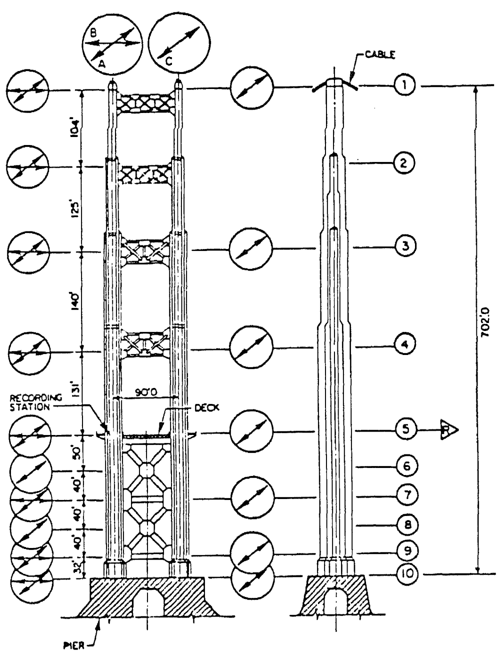

Fig. 3 SAN FRANCISCO TOWER WITH MEASUREMENT STATIONS SHOWN

The bridge consists of a mainspan of 4,200 ft. (1,280m) and two sidespans of 1,125 ft. (343m) each. The spans are suspended from the main cable, which is supported by the two towers. Both towers are 690 ft. (210m) high from the pier to the base of the saddle castings, and rise 746 ft. (227m) above the water. An elevation is presented in Fig. 1. Fig. 2 shows a typical span cross-section, and Fig. 3 details one of the towers. Except for anchorages, approaches and tower footings, the bridge is symmetric about mid-span.

AMBIENT VIBRATION INSTRUMENTATION

Fig. 4 shows a block diagram of the instrumentation used to measure the ambient vibrations of the Golden Gate Bridge. Components of this system are described below. The measurement system was assembled, tested and calibrated at Kinemetrics prior to the field measurements.

Sensors

Typically seismometers have been used in ambient vibration measurements because of their high sensitivity and ease of use. Abdel-Ghaffar and Housner (Ref. 2) used seismometers in their ambient vibration study of the Vincent-Thomas Bridge. However, most seismometers have flat response down to only one or two hertz, limiting their usefulness at low frequencies. Large, flexible structures often have modal frequencies below one hertz. Also, long cables can attenuate the seismometer outputs and increase the noise level, as the voltage output is very low.

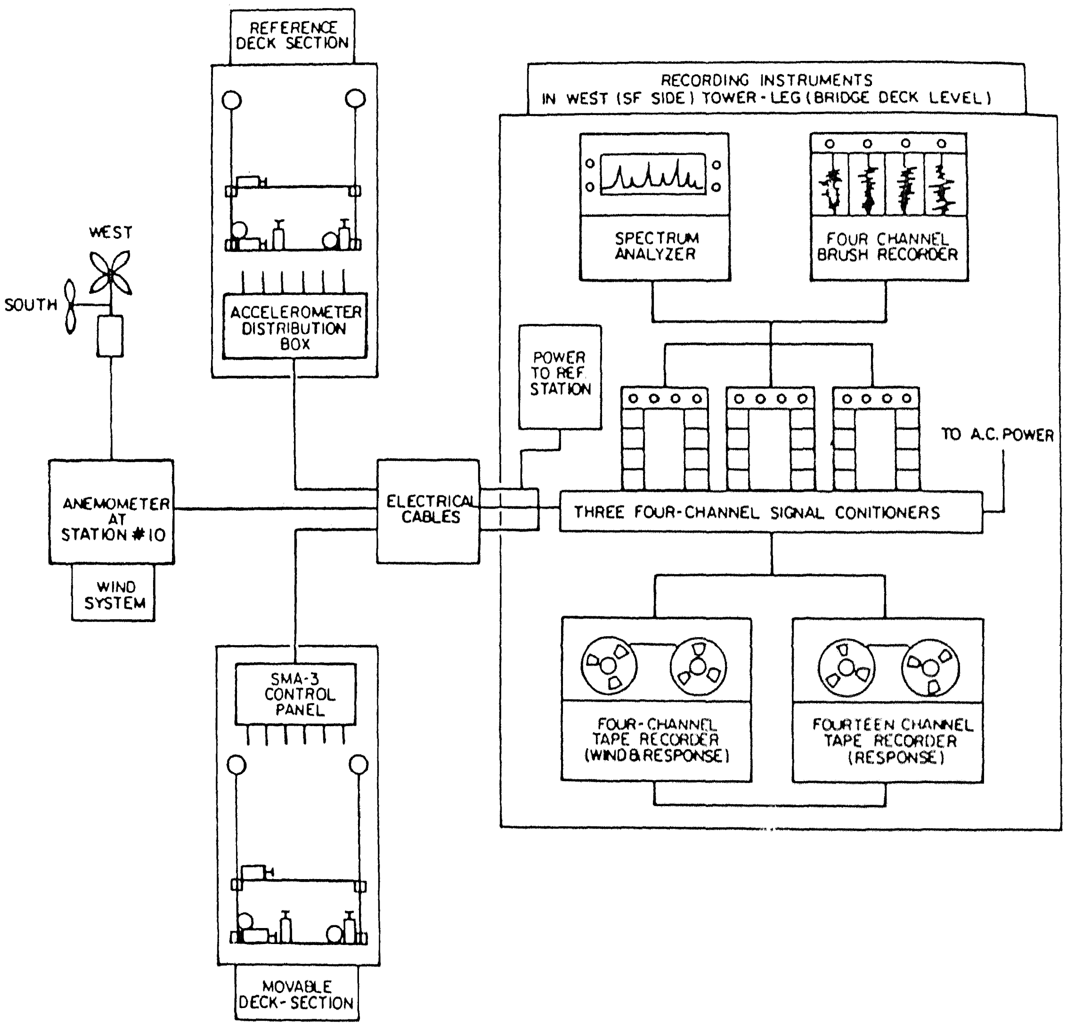

Fig. 4 AMBIENT VIBRATION MEASUREMENT SYSTEM

Servo accelerometers were chosen for use in this project, as modal frequencies well below one hertz and several thousand foot cables were expected. Such sensors have been used on several previous ambient vibration studies. Benuska et. al. (Ref. 3) used force-balance servo accelerometers to measure the wind response of an 802 ft. high concrete chimney. Rainer and Van Selst (Ref. 1) used servo accelerometers in their study of the Lion's Gate Suspension Bridge.

Bridge response was measured using Kinemetrics Model FBA-1 and FBA-11 force-balance accelerometers. These sensors have a flat (-3dB) response between DC and 50 HZ, and have a high (2.5 volt/g) output. Their dynamic range is 100 dB, allowing vibration as low as 10^{-5}g to be measured. Cable lengths of thousands of feet will not affect the output of these sensors. Up to 12 accelerometers were used to simultaneously measure motion at various locations.

Mounting the accelerometers on the bridge proved to be a problem for several reasons. First, it was required that no damage be done to the paint or the metal of the bridge, so bolting or glueing the sensors to the bridge was not possible. Second, the bridge surface was almost always wet because of the salt-laden fog. Finally, because of the number of sensor locations the method of attachment needed to be quick. Plaster-of-paris was found to be ideal for this application. It set quickly, even in standing water, and adhered well to the painted metal. When the sensors were removed, the remaining plaster could easily be chipped off of the surface, leaving no trace.

Wind speed was measured simultaneously with bridge response using an R.M. Young UVW anemometer system. Only two axes of this triaxial device were used; these were oriented horizontally. The anemometers were mounted on an eight foot mast, which was attached to the bridge using clamps.

Cabling

If individual cables had been used to connect each of the 12 accelerometers to its control/power panel in the recording station, over 18,000 ft. of cable would have been required for the main and sidespan measurements. The logistics of moving this cable would have been formidable, and the cost prohibitive. Therefore, the cable system shown in Fig. 4 was designed. Each sensor required power, test signal, and shielded output conductors. The reference accelerometers (which remained in the same place throughout the span measurements) were connected by short cables to a junction box. This junction box was connected by a 1000 ft. cable to the central recording station. Power and test signals were provided from the recording station.

A portable control/power panel was used for the remaining accelerometers (which were moved to various locations along the bridge). Short cables connected these sensors to the control/power panel. A 2250 ft. cable carried the signals from the control/power panel to the recording station.

Using the cabling system described above, only slightly more than 4000 ft. of cable was required for the accelerometers. The short cables connecting each accelerometer to the junction box or control/power panel made the installation and removal of the instrumentation much simpler than it would have been if individual long cables had been used during the span measurements.

For the tower measurements, a combination of this cable system and individual sensor cables was used.

Signal Conditioning

Signals from the accelerometers were amplified and filtered using Kinemetrics' Model SC-1 signal conditioners. Data were high-pass filtered at 0.03 HZ to remove DC offsets. Signals above the frequency range of interest were removed by low-pass filtering. Filter corner frequencies of 5 HZ for the span and 15 HZ for the tower measurements were used; filters for the various data channels were matched using a real-time spectrum analyzer. Amplifier gains were set in the field to allow maximum use of the dynamic range of the recording system.

The wind speed data from the two anemometer channels were not conditioned, as both the signal level and frequency content were adequate for direct recording.

Recording

Because of the extreme environmental conditions and the need for on-site data review, an analog recording system was chosen over an equivalent digital system. Up to 12 channels of data were recorded simultaneously on a Honeywell Model 5600E 14-channel FM tape recorder. To improve dynamic range at low frequencies, the fourteenth channel was used for flutter compensation; with flutter compensation, the dynamic range of the recorder was approximately 50 dB. During the span measurements, a Hewlett-Packard Model 3960A 4-channel FM tape recorder also recorded additional channels of data.

While being recorded on tape, selected data channels were monitored by a Gould Model Brush 440 4-channel chart recorder. This recorder was also used to observe signal levels while adjusting the amplifier gains.

A Hewlett-Packard Model 3582A real-time Spectrum Analyzer was used to observe the frequency content of the data. On-site estimation of modal parameters was possible with this instrument, as transfer functions between channels could be calculated.

FIELD PROGRAM

The eight-man team which carried out the experimental work consisted of four from Princeton University and four from Kinemetrics. Additional man power was provided by the Golden Gate during the main and sidespan tests and to operate the tower elevator during the tower tests.

The field work began on June 14, 1982. The recording instrumentation (see Fig. 4) was set up inside the West leg of the San Francisco tower at bridge deck level on a platform in the vacant elevator shaft. In order to protect the instrumentation from the extreme humidity, a small electric heater was installed near the recording instrumentation. This heater was used only during the day when people were present; at night a single light bulb was adequate for keeping moisture from condensing on the instrumentation.

During the next ten days measurements were made of both span and tower vibrations. These two sets of measurements are described below. In order to reduce the amount of data required, symmetry in the bridge response was assumed. Only the South half of the bridge was studied.

Mainspan and Sidespan Measurements

The vertical, longitudinal (along span), and transverse (across span) motion of the mainspan and sidespan on the South half of the bridge were measured using 12 channels of accelerometers. At each of the 18 stations shown in Fig. 1, six accelerometers were installed. The positions and sensitive directions of these six accelerometers are shown in Fig. 2.

Station 8 was the reference station for all of the span measurements. Signals from these six accelerometers were recorded on Channels 1 through 6 of the Honeywell 5600E tape recorder.

The other six accelerometers were in turn mounted at Locations A through F at each of the other stations. The motorized scaffold inside the span was used to move the accelerometers and cable from station to station. At each station, the accelerometers were mounted, cables were connected, signals were checked and data were recorded. The six "moving station" accelerometers were recorded on Channels 7 through 12 of the tape recorder. A total of 108 components of main and sidespan motion were measured.

The anemometer was attached to the bridge railing on the West side (prevailing wind side) near Station 10, with an effective height above the deck of 11 ft. Wind speed data were recorded along with one channel of reference acceleration on the Hewlett-Packard tape recorder.

One hour of ambient vibration data were recorded at each of the mainspan stations. Thirty minutes of data were recorded at each of the sidespan stations except Station 17, for which one hour of data was recorded. At the end of the span measurements, a channel calibration was performed on the amplifier, filter and recording system.

Tower Measurements

The motion of the San Francisco (South) tower of the Golden Gate Bridge was measured using 9 channels of accelerometers. These sensors were oriented in the same coordinate system (longitudinal and transverse) as was used for the span measurements. At the ten stations shown in Fig. 3, accelerometers were mounted at positions A, B and C as shown. At some stations only one or two sensors were used due to access problems.

Before any tower measurements were taken, the low-pass filters on the signal conditioners were reset to 15 HZ and a calibration run was recorded. Sensors were then placed at the tower reference station (Station 5) in positions A, B and C. These were recorded on Channels 7 through 9 of the 14-channel tape recorder. With the span reference station (Station 8) still in place, 1/2 hour of data were recorded.

The anemometer was then moved to the highest point of the West saddle on the tower. These wind sensors were now the highest objects on the bridge. The two wind speed signals were moved to Channels 10 and 11 of the 14-channel recorder; the Hewlett-Packard tape recorder was not used for the tower measurements.

Accelerometers 1 through 6 were then moved to the various locations on the tower. The tower elevator provided transportation to the various levels of the tower. Cables were routed to the recording station through the unused elevator shaft in the West side. Three or four tower stations were included in each of the four data runs; in all 25 components of tower motion were measured. Thirty minutes of data were recorded for each run.

DATA DIGITIZATION

To facilitate computer processing of the vibration data, the analog data recorded on the two tape recorders were digitized at Kinemetrics following the field program. A Kinemetrics Model DDS-1105 Digital Data Acquisiton System was used to digitize the span data at 50 samples per second and the tower data at 100 samples per second. Krohn-Hite Model 3202 filters were used to low-pass filter the data before digitization to prevent aliasing. These were 24dB per octave butterworth filters, with corner frequencies of 25 HZ (span data) and 50 HZ (tower data).

CONCLUSION

During the field portion of the ambient vibration measurements of the Golden Gate Bridge, many problems were encountered in the design of the instrumentation and in the data acquisition. These included sensor choice, sensor mounting, cable design, and protection from environment. The solutions to these problems have been discussed.

Extensive, high-quality data were acquired during the field measurements. These data are expected to provide researchers and analysts with information of exceptional quality for years to come.

REFERENCES

1. Rainer, J. H. and Selst, V. A., "Dynamic Properties of Lions' Gate Suspension Bridge", ASCE/EMD Specialty Conference on Dynamic Response of Structures: Instrumentation, Testing Methods and Systems Identification, University of California, Los Angeles, March 30 and 31, 1976.

2. Abdel-Ghaffar, A. M., and Housner, G. W., "Ambient Vibration Tests of Suspension Bridges", Journal of Engineering Mechanics Division, ASCE, Vol. 104, No. EM5, Proc. Paper 14065, October, 1978, pp. 983-999.

3. Benuska, K. L., Matsummoto, G. Y., Killam, E. H., and Diehl, J. G., "Structural Characterization of Concrete Chimneys," ASCE/EMD Specialty Conference on Dynamic Response of Structures: Experimentation, Observation, Prediction and Control, Atlanta, Georgia, January 15 and 16, 1981.