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Aerodynamic Monitoring of the Cable-Stayed Mississippi River Bridge

Contrôle de la réponse aérodynamique d'un pont à haubans le Mississippi

Überwachung des aerodynamischen Verhaltens einer Schrägseilbrücke über der Mississippi

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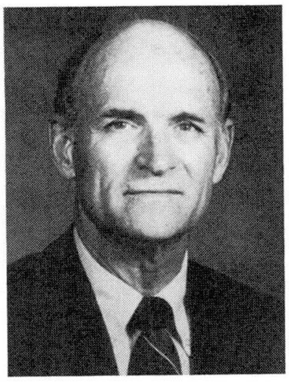

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SUMMARY
Results of monitoring of the aerodynamic response and wind climate of a cable-stayed bridge across the Mississippi River at Luling, Louisiana, USA, are presented. Typical measurements made of wind spectra and wind induced motions of the cable stays and bridge deck are compared with predictions.

RESUME
Les résultats d'un programme de contrôle et de mesures de la réponse aérodynamique d'un pont à haubans sur le Mississippi près de Luling en Louisiane (USA) et des vents sur le pont sont présentés. Des valeurs typiques des spectres mesurés des vents et des déplacements des haubans et du tablier causés par le vent sont comparés aux valeurs prédites.

ZUSAMMENFASSUNG
Die Resultate der Ueberwachung von Windverhältnissen und Bauwerksreaktion infolge Wind bei der seilverspannten Brücke über den Mississippi in Luling, Louisiana, USA, werden vorgestellt. Typische Messwerte der Windspektren, sowie der Bewegungen von Pfeilern und Brückenträgern werden mit den vorausberechneten Werten verglichen.

1. INTRODUCTION

Early in the preliminary design of the cable-stayed Mississippi River bridge at Luling, Louisiana, it was decided that the bridge should be instrumented to measure its dynamic response to wind and to obtain the characteristics of the wind at the site. The bridge was to be erected in an area exposed to hurricane winds. Potentially, there were opportunities for enhanced understanding of the aerodynamic response of the cable stays and deck under moderate and extreme winds.

The bridge was completed in 1984 and data acquisition began that same year. The responses presented here cover a range of wind speeds up to 15.6 m/s. The bridge has not yet experienced a hurricane.

The work described herein was sponsored by the Louisiana Department of Transportation and the United States Federal Highway Administration.

2. DESCRIPTION OF THE BRIDGE

The Mississippi River bridge at Luling, Louisiana is the first large steel cable-stayed structure to be built in the United States. It consists of a five-span superstructure, made entirely of weathering steel. Measuring 372.5 m center-to-center between support towers, the navigation channel span was the longest of its kind in the western hemisphere at the time it was opened to traffic. Worldwide, the channel span is the second longest of its type, the longest being the 404 m span across the Louri River at St. Nazaire in France. The Luling bridge lies in the North American hurricane belt and is designed to withstand the static and dynamic loads of hurricane force winds.

Deck support is provided by continuous twin trapezoidal box girders having a constant depth of 4.27 m. For the main span there are six rectangular cross girders where additional support is provided by the connection of cable stays. To improve aerodynamic performance, the main span is equipped with fairing plates. The total length of the bridge is 837 m; while the deck measures 25 m in width providing four lanes of traffic flow plus outside shoulders. The towers are of all-welded cellular construction and rise 122 m above the mean low water level of the river. A number of these details are summarized in Fig. 1.

The cable system consists of 12 stays per tower arranged in two identical radiating patterns. Each stay contains two or four cables. Each stay terminates both at the cross girder and at the tower top in a Hi-Am anchorage. The individual cables are built from parallel 0.635 cm diameter wires bundled in groups of 103, 211, 271 or 307 wires, depending on load and location. These wires are cold drawn stress relieved and prestressed with a design strength 45% of the ultimate. The bundle is wrapped with 0.635 cm diameter wire on a 1.83 m pitch along its entire length. This wrapping contained the bundle during shipping and installation and holds a polyethylene pipe away from the wire bundle, providing an annulus which is filled with grout. The polyethylene pipe and grout provide weather protection for the bundle. Grout was injected after the stays had been tensioned on the bridge.

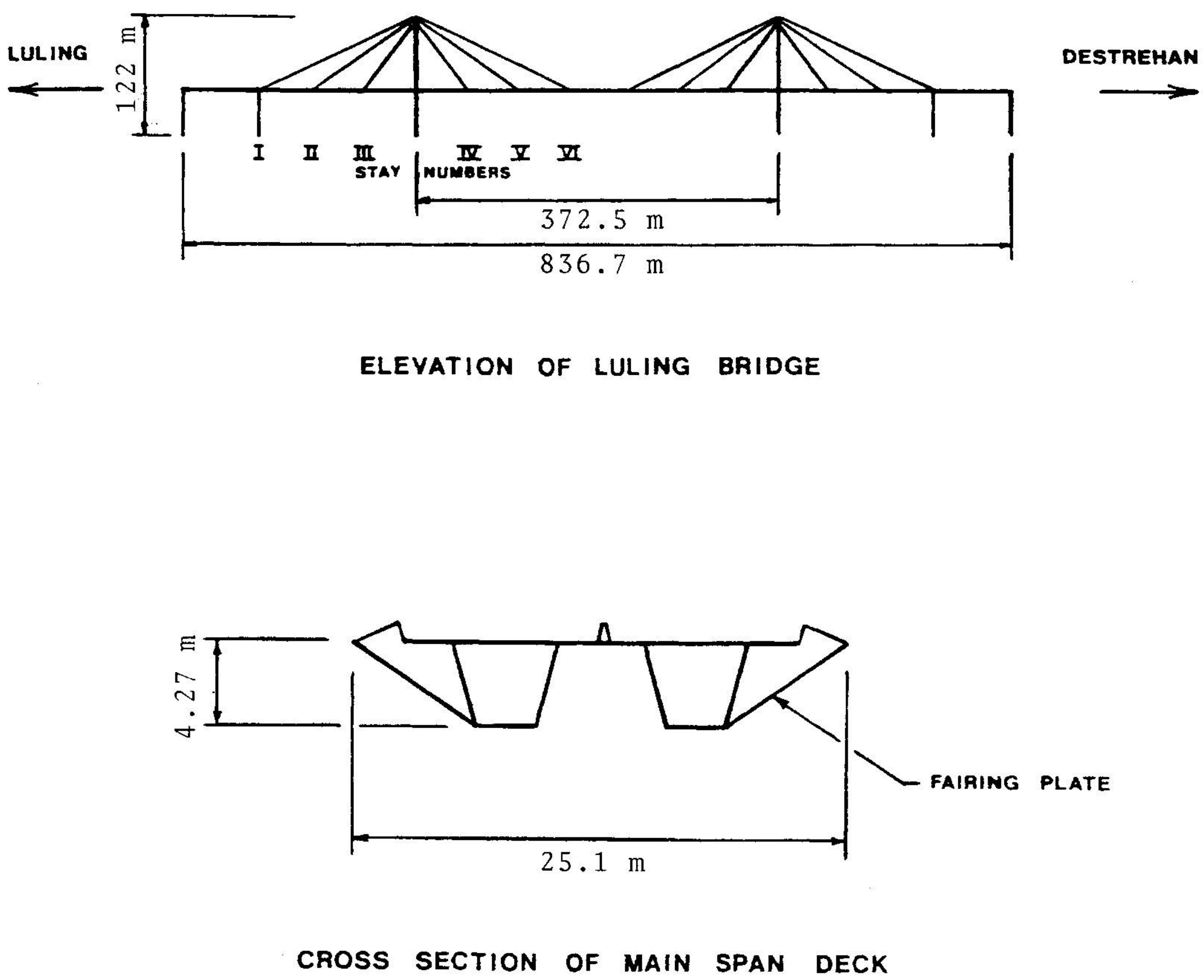

Fig. 1 Bridge details

3. INSTRUMENTATION

The upriver stays on the Luling side of the bridge were instrumented with pairs of accelerometers. Each pair of accelerometers was mounted with sensitive axes mutually perpendicular and also perpendicular to the axis of the cable. The displacement spectrum of the major axis of the eliptical path of each pair of accelerometers was computed from acceleration data.

Acceleration of the bridge deck was monitored at the center of the two approach spans on the Luling side of the main span and at the center and quarter points of the main span. These data provided displacement spectra of the vertical and torsional modes of deck motion. Anemometry located at the same points as the deck monitoring equipment provided measurements of the three mutually perpendicular components of the wind. The top of the tower supporting the instrumented stays also was provided with an accelerometer in order to record the tower motion in the direction of the longitudinal axis of the bridge. Detailed descriptions of the data acquisition instrumentation and techniques, as well as the computer software used for data reduction and analysis, may be found in [1] and [2].

4. STAY MOTION

As an example of the data acquired from the stays, Fig. 2 is a graph of the motion of the longest backstay in a wind having an average speed of approximately 4 m/s and a turbulence intensity of 15% [3]. These data were recorded at an accelerometer station located at a point equivalent to 11% of the stay span length above the bottom anchorage point of the stay, and processed by a computer to achieve the desired spectral format. The position of the accelerometer stations on the stays was selected for convenience and accuracy in estimating the antinodal amplitudes of the first twenty modes of cable motion [4]. The equally spaced peaks in Fig. 2 represent the natural frequencies of the stay as it responds primarily to vortex shedding. The peak heights represent a 13.65 minute average of the peak amplitudes of the major axis of the elliptical displacement trajectory at the various frequencies. Measured fundamental frequencies of the stays were in all cases slightly less than the analytically predicted values, with the greatest error being 9.3% [4].

The stay numbering system is indicated in Fig. 1 where the longest backstay is identified as I and the remaining stays are numbered sequentially through the longest forestay which is identified as VI.

The aerodynamic response of cable stay I to wind is summarized in Fig. 3. The figure is a plot of antinodal displacement amplitude versus mode number or, indirectly, vibratory frequency. Additional parameters shown on the figure are the average wind speed during the time of the measurement and the horizontal direction of the wind. In this connection, a value of the angle θ equal to zero degrees indicates a wind blowing perpendicularly to the longitudinal axis of the bridge and coming from the upriver direction; 90° indicates a wind originating from the Luling side of the river and oriented along the longitudinal axis of the bridge.

The mode number or frequency necessary to resonant vibration of the cable stay with vortex shedding, that is, aeolian vibration, is indicated at each wind speed by a black circle. These frequencies were calculated by assuming a Strouhal number equal to 0.20, and using the measured frequencies of the stays as well as the component of the mean wind which was perpendicular to the stay. Where the circles do not appear on the graph for a particular wind speed, the critical frequency was greater than 20 Hz. The instrumentation system does not respond beyond 20 Hz.

As the wind speed and forcing frequencies increase, the response frequencies increase and their amplitudes decline. At the lower frequencies - second and third modes - the 13.65 minute average antinodal displacement amplitudes associated with vortex shedding are less than 1.0 mm, while at the higher mode numbers the amplitudes are less than 0.2 mm. Using the methods set forth by Doocy, et al, [5] these amplitudes suggest bending stress amplitudes in the individual rods of the stays of less than 1050 kN/m^2. Such stress levels are not likely to pose fatigue problems. It is also unlikely that greater displacements or stresses caused by vortex shedding will be measured in future studies since the large displacements induced by vortex shedding are associated in these data with wind speeds of the order of 4.5 m/s or less.

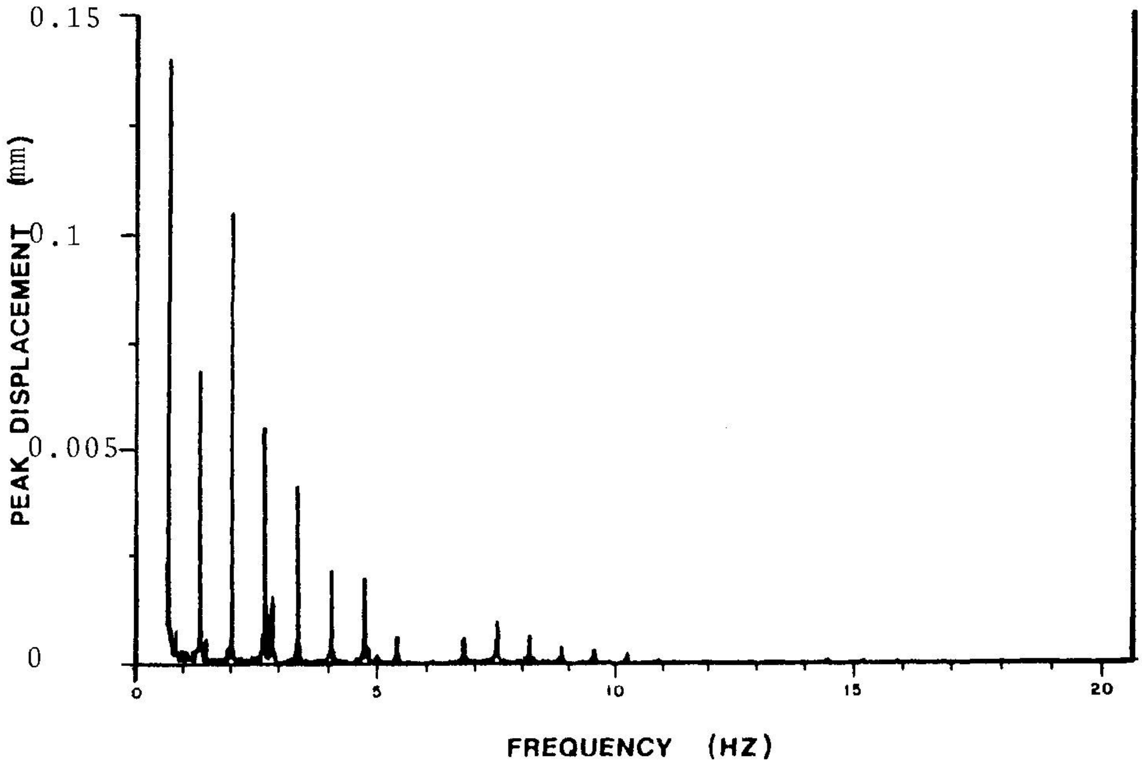

Fig. 2 Displacement spectrum of inboard cable of stay I for a wind speed of 4 m/s

Based on the correlation model described by Blevins [6], these data also suggest that the logarithmic decrement of the cable stays ranges from 0.03 at the lower frequencies upward towards 0.10 at the higher levels. In magnitude and functional dependency upon frequency such values are comparable to data reported by Edwards and Livingston for self damping electrical conductors [7].

The largest measured amplitudes occur in the fundamental mode of the longest backstay at wind speeds in excess of 10 m/s. As will be demonstrated below these large amplitudes in the motion of the stays coincide with the onset of deck resonance in the vertical mode caused by shedding of vorticies from the bridge. The largest recorded 13.65 minute average displacement amplitude of the stay is approximately 3.0 mm at a mean wind speed of 14 m/s. Because of the low frequency of the motion, this amplitude should produce bending stresses of approximately 1140 kN/m^2 at the socket faces.

Three of the six instrumented stays, I, IV and V, are comprised of four identical cables arranged on a pattern measuring 60 cm by 150 cm horizontally. The lower two cables of stays I and V were instrumented primarily to observe the effects of wake induced vibration. Some evidence of wake induced excitation was obtained. For the first three modes of motion of stay I, Fig. 4 presents a plot of the ratio of the displacement amplitude of the leeward cable to that of its windward companion. Nominally, 10 to 25% greater amplitudes are in evidence on the leeward stay. In the worst case there is a 40% increase in activity associated with the 14 m/s wind speed. However, these large percentage increases in amplitude are associated with very low levels of displacement, as may be seen by referring to Fig. 3.

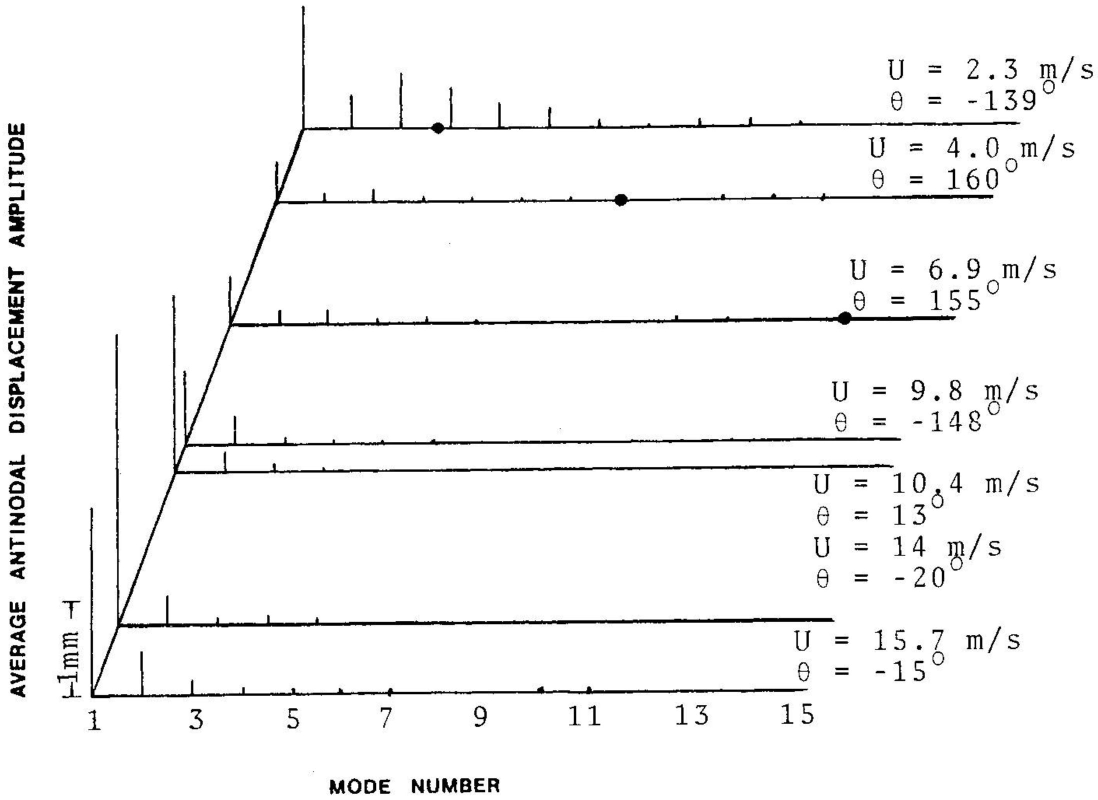

Fig. 3 Aerodynamic response of stay I

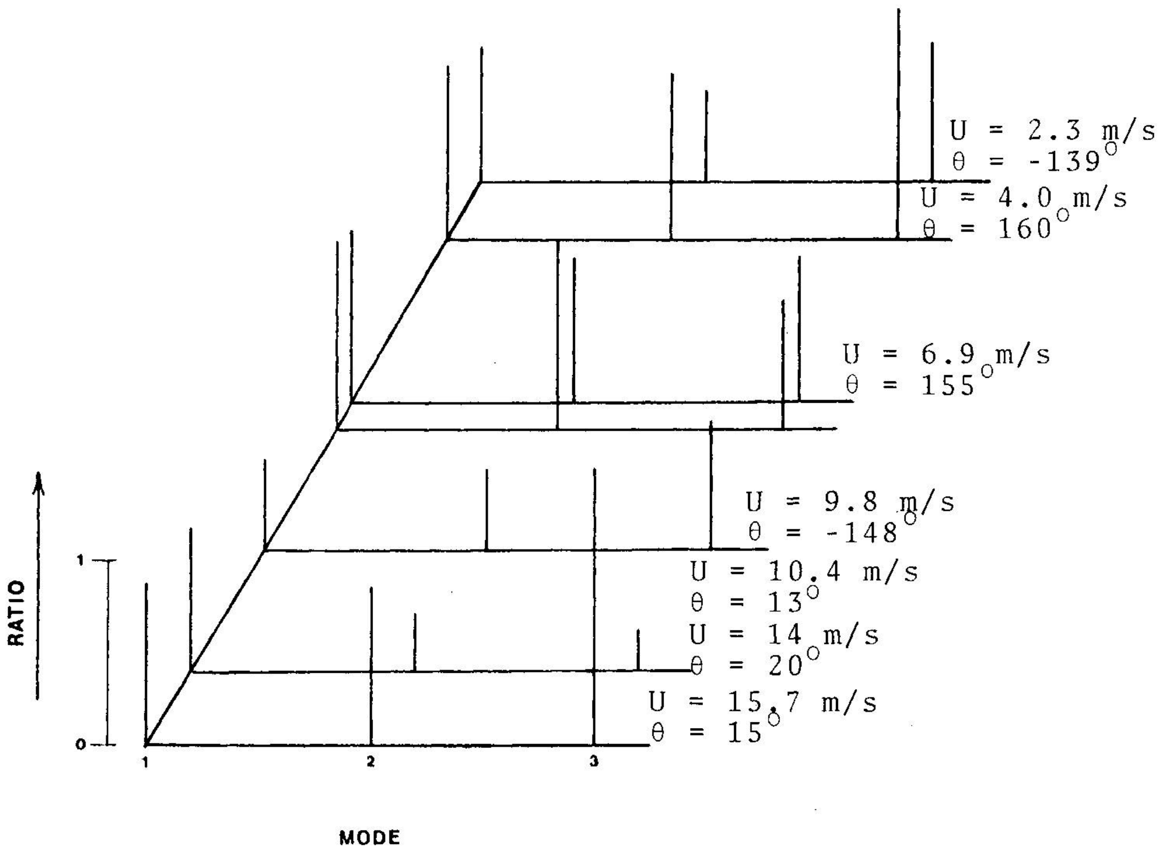

Fig. 4 Ratio of downwind to upwind displacement of stay I

5. DECK MOTION

Spectra of the peak vertical motion of the center section of the main span were obtained for various wind speeds and directions [3]. The fundamental frequency of the first vertical mode of deck motion measured 0.35 Hz; this is to be compared with a value of 0.369 Hz which was anticipated during the preliminary design and wind tunnel studies for the bridge [8].

The variation of the vertical, first mode displacement amplitude of the bridge deck as a function of position on the bridge and wind speed is shown in Fig. 5. This figure summarizes data taken from a number of spectra. Station 4 identifies the instrumentation located at the center of the main span; Stations 3 and 5 are at the quarter points of the main span; and Stations 1 and 2 are at the center of the two side spans on the Luling side of the main span. The abrupt increase in displacement amplitude between 9.8 and 10.4 m/s heralds the onset of resonance between the first vertical mode of deck motion and the shedding of vorticies from the deck. In the most common case, the resonance would cease at some wind speed beyond 15 m/s, and the amplitudes would decline [8]. Thus, it is not clear that the maximum displacement amplitudes of this resonant condition have been measured in the current series of observations. However, at this frequency the time averaged maximum measured displacement amplitude of 3.6 mm is equivalent to an acceleration of 0.00175g, far below the levels of 0.02g which has been suggested as the point where bridge users begin to feel discomfort because of deck motion.

Comparison of Fig. 5 with Fig. 3 indicates that the increase in the displacement of the cable stay in its first mode is coincident with wind speeds of 10.4 m/s and above. Thus, it appears that the increased activity may arise in the resonant interaction of the vertical mode of deck with the shedding of vorticies. There also remains the possibility that the wind has exceeded a critical level necessary to the onset of stay galloping because of departures from circularity in cross section or eccentricities in aerodynamic center and center of rotation.

Estimates of the critical wind speed for vortex excitation of the deck vertically and the amplitude of the resultant motion were prepared during the design phase of construction of the Luling bridge [8]. The estimated values were 7.5 m/s and 6.6 cm at mid span. These estimates rest on the conservative assumptions of bridge damping at one percent, coherent vortex shedding along the entire length of the span, and a uniform, low turbulence intensity wind normally incident upon the bridge. As shown in Fig. 5 the vertical resonance begins between the 9.8 and the 10.4 m/s wind speeds. Neither of these are normally incident winds; their angles to the axis of the bridge are 58° and 77° , respectively, producing components of the wind normal to the bridge of 8.3 and 10 m/s. Thus, the wind tunnel indications of the critical wind speed may be accurate, although additional data are needed to obtain more precision in this regard. Clearly, the estimate of displacement amplitude was high. However, it is more than likely that the damping of the bridge is greater than the conservative figure of one percent [9], and most unlikely that the shedding is coherent along the length of the bridge. Unfortunately, current protocols do not include measurements of bridge damping nor the opportunity to estimate the degree of coherence of vortex shedding along the bridge length.

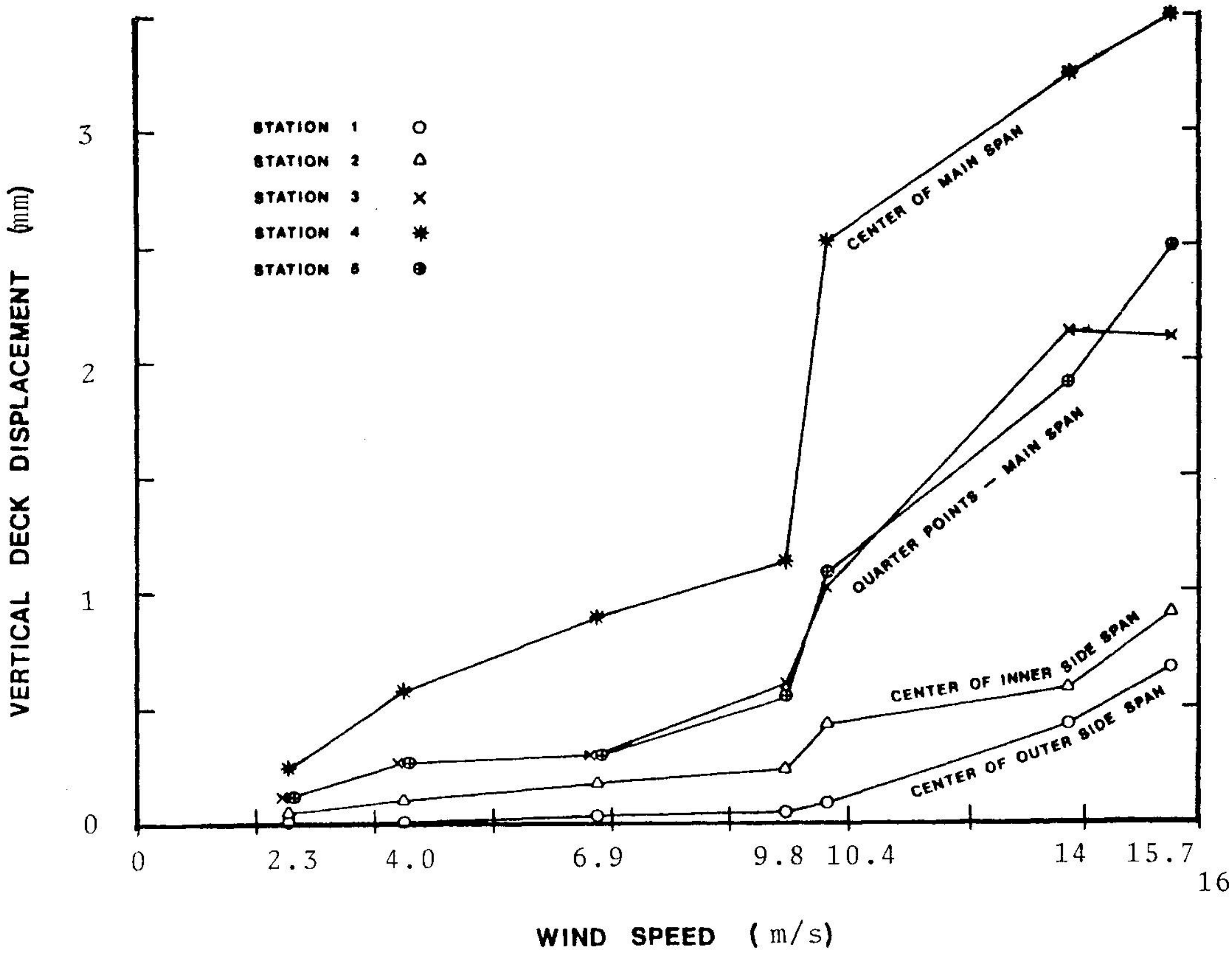

Fig. 5 Vertical deck displacement

The torsional displacements of the bridge deck were quite small by comparison with the values associated with the vertical modes at all wind speeds encountered. The first natural frequency of the torsional mode of the deck was measured at 0.937 Hz. This is to be compared with a pre-construction estimate of 1.238 Hz.

The contribution of the torsional displacement may be seen in the representation of Fig. 6. This figure properly scales the total displacement at the center of the main span and at the deck edge. The proportion of the height of the vertical mode displacement and the height contribution to the edge of deck from the torsional mode are preserved. Differences in the frequencies of the two modes are readily apparent. In all cases observed the contribution of the torsional mode was on the order of 10% of the total displacement of the edges of the bridge deck. There was no evidence of torsional resonance with the shedding of vorticies from the girders, which is consistent with design studies indicating excitation of the torsional mode at wind speeds in the vicinity of 32.5 m/s [8].

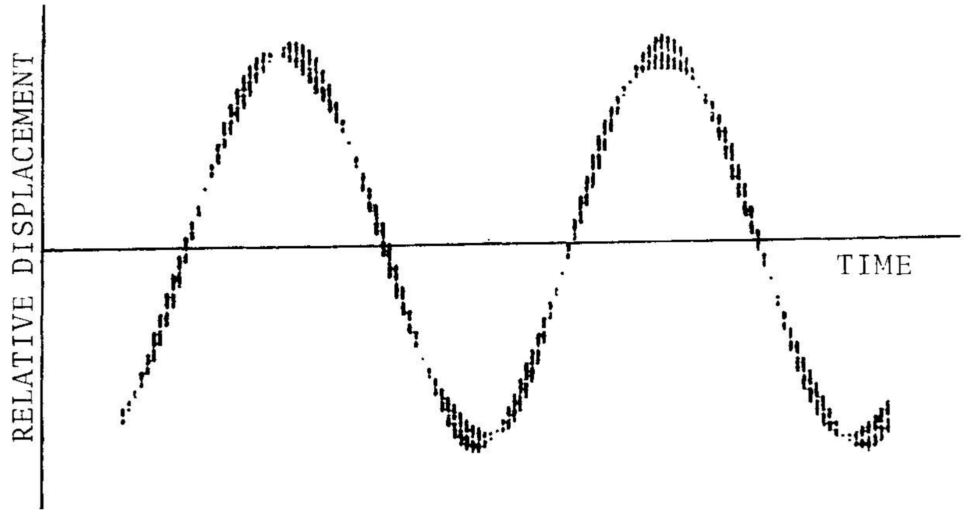

Fig. 6 Relative vertical and torsional displacements

6. TOWER MOTION

An accelerometer was placed in the top of the tower carrying the instrumented stays. The orientation of the device provides measurements of tower motion parallel to the axis of the bridge. Data were taken during the same time as the previous spectra for the vertical and torsional motion of the bridge deck. The largest time averaged displacement amplitude occured at a frequency of 0.350 Hz which coincides with the frequency of the deck in its first vertical mode. Clearly, this component of the tower motion is a part of the first mode vibration of the entire structure moving in response to the shedding of vorticies from the deck and supporting girders. At this wind speed, displacements for other modes were negligible.

None of the stay spectra show any response in the vicinity of 0.35 Hz. This suggests that the tower is largely coupled to the deck through the axial, and not the transverse, mode of cable vibration. Because the transverse vibrations of the stays were a matter of first priority, the placement of the accelerometers on the cables is such that axial motion of the cable elicits no response.

Amplitudes of the tower motion at the frequency of the vertical deck vibration are shown in Fig. 7 as a function of windspeed. Although the onset of deck resonance is still apparent in this figure, it is not as pronounced as in the graphs of deck displacement.

The changes in cable stay tension and stress because of the combined motion of deck and tower are a matter of interest because of the possibility that the fatigue limit of the stay rods might be exceeded. An estimate of this change may be obtained by assuming that the longest backstay, Stay I, is fixed in place at its lower end; such an assumption is at least partially justified by the fact that this stay is connected to the bridge at a pier; the other backstays are attached to cross beams on the first approach span where greater flexibility is available. Also it may be assumed conservatively that the tower does not foreshorten under increased compressive load, and that all elongation of the backstay is drawn from the axial mode of stay motion, without effect upon transverse sag. Under these assumptions the maximum tower displacement at 0.350 Hz, which was measured as 0.9 mm, produces a stress amplitude of 1170 kN/m^2 in the cable rods, again an insignificant variation vis-a-vis fatigue.

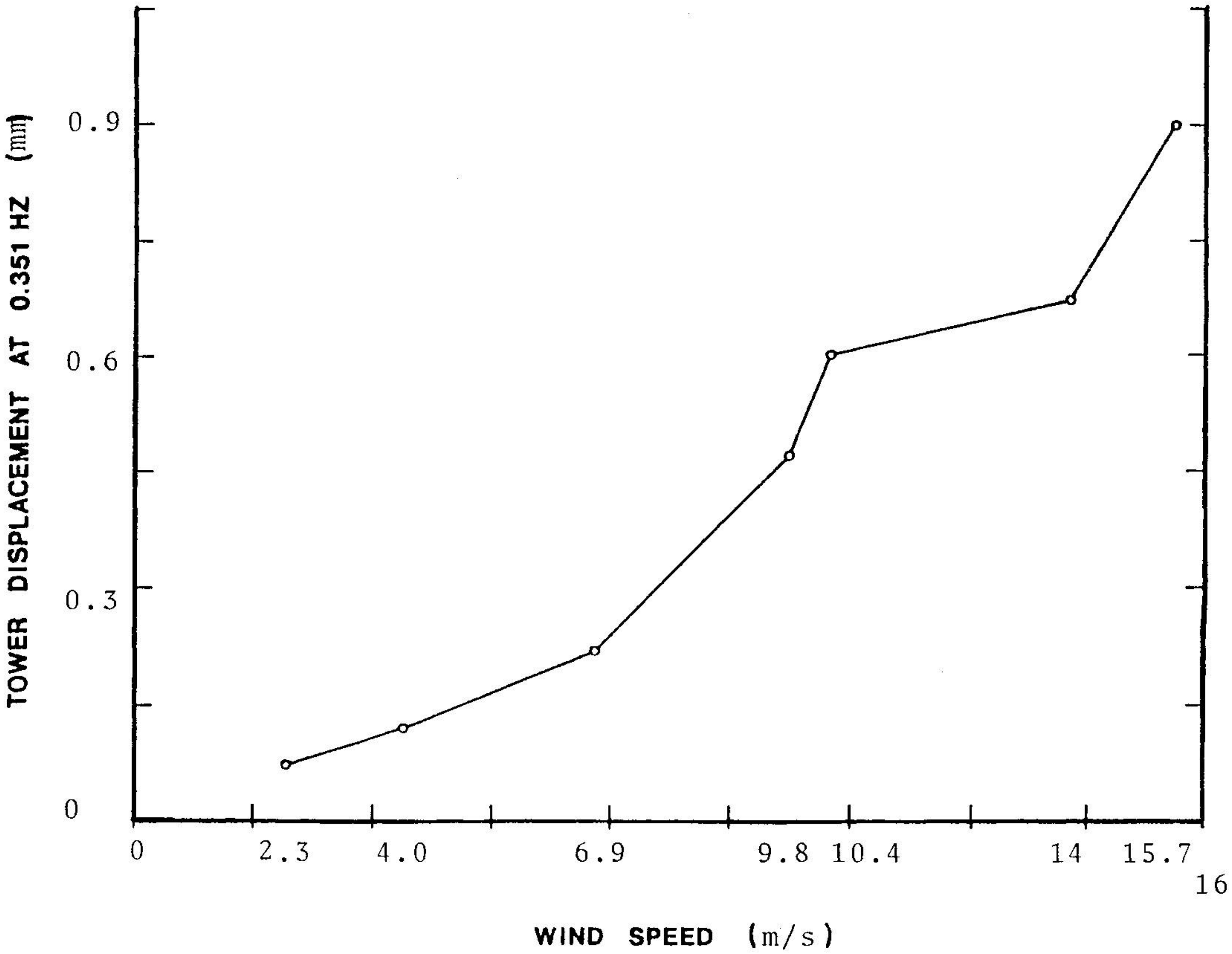

Fig. 7 Tower displacement

7. WIND CHARACTERISTICS

Some of the principle properties of the wind which produced the responses in Fig. 3, Fig. 4, Fig. 5, and Fig. 7 are summarized in Table 1. The mean wind values averaged over 13.65 minutes are given along with their horizontal and vertical angles. Winds originating from the upwind direction normally incident upon the bridge are assigned values of $\theta = 0$. The angle θ is measured positively as it turns towards the Luling end of the bridge. The angle ϕ is measured from the perpendicular; values of ϕ of less than 90° indicate an upward component in the mean wind velocity. The turbulence intensity is of interest because of its possible role in eliminating coherent shedding of vorticies from the deck and cable stays. The declining turbulence levels shown with increasing wind speed reflect in part the elimination of currents driven by thermal convection. At the 4% level, the turbulence intensity is approaching the kinds of turbulence associated with wind tunnel tests where 0.5 - 1.0% may be expected.

Wind Speed m/s	θ,degrees	φ,degrees	Turbulence Percent	Roughness Factor[10]
2.28	-139.0	88.9	20.6	-
4.02	160.0	84.6	12.7	0.0153
6.93	155.0	87.0	7.9	0.0059
9.79	-148.0	88.0	6.1	0.0030
10.4	12.9	85.8	5.6	0.0029
14.0	-19.6	87.0	4.1	0.0021
15.7	-14.6	87.0	4.0	0.0017

Table 1 Wind Characteristics

Representative measured and theoretical wind spectra along the wind direction for a wind speed of 9.6 m/s are shown in Fig. 8. The smooth curve is the spectrum suggested by Davenport [10]. At wave number values of the order 10^{-3} inverse meters, there remains considerable uncertainty, because at this wind speed the associated period of the low frequency waves is of the order of two minutes and the sample period is only 13.653 minutes. With the exception of the low wave number portion of the curve, the Davenport spectrum provides a reasonably good approximation to the spectrum measured at the bridge site, although it does overestimate the high frequency components, as suggested by Simiu and Scanlan [11].

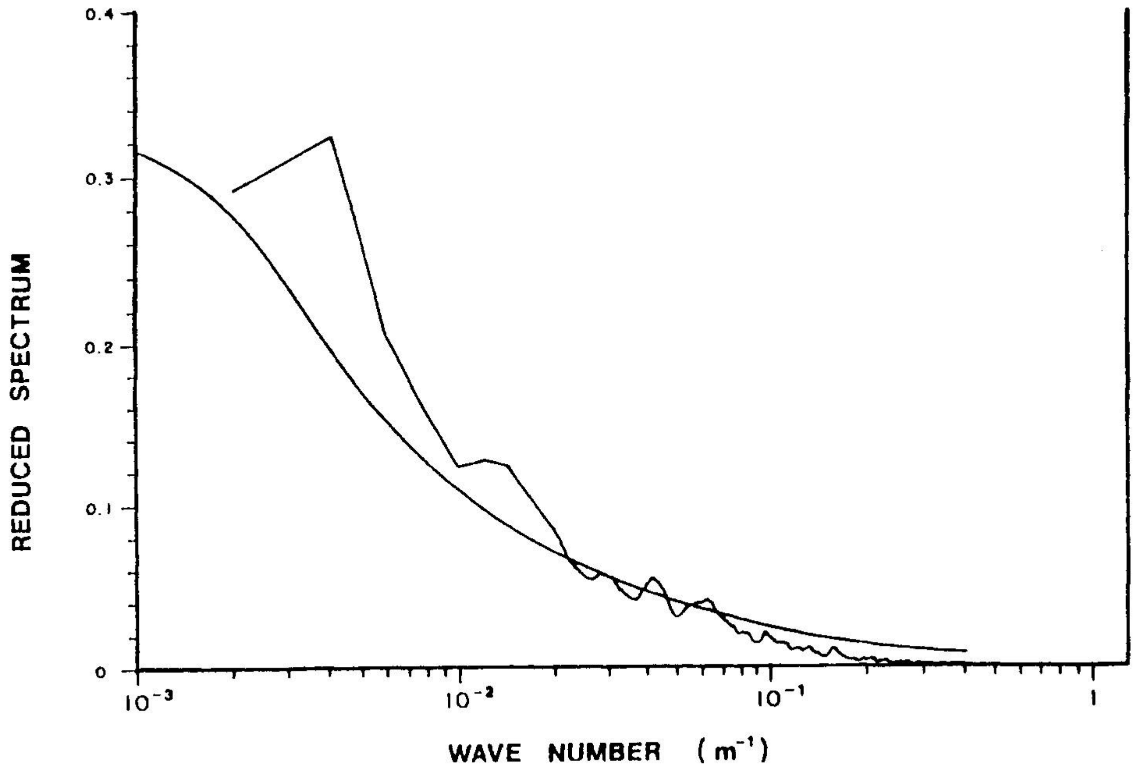

Fig. 8 Wind spectra

The coherence of the longitudinal component of the turbulence is shown in Fig. 9. Data for this figure were taken from the anemometers at the center and quarter point of the main span for a normally incident wind speed of approximately 10 m/s. Curves for decay constants equal to 1.5 and 2.0 are drawn on the figure. These values are to be compared with values of 6 and 7 proposed by Davenport, and with values of 3.5 at 21 m/s and 8.8 at 33 m/s quoted by Simiu and Scanlan [11] from the work of Shiotani. These findings serve to further reinforce their assertion that decay constants are functions of the mean wind speed.

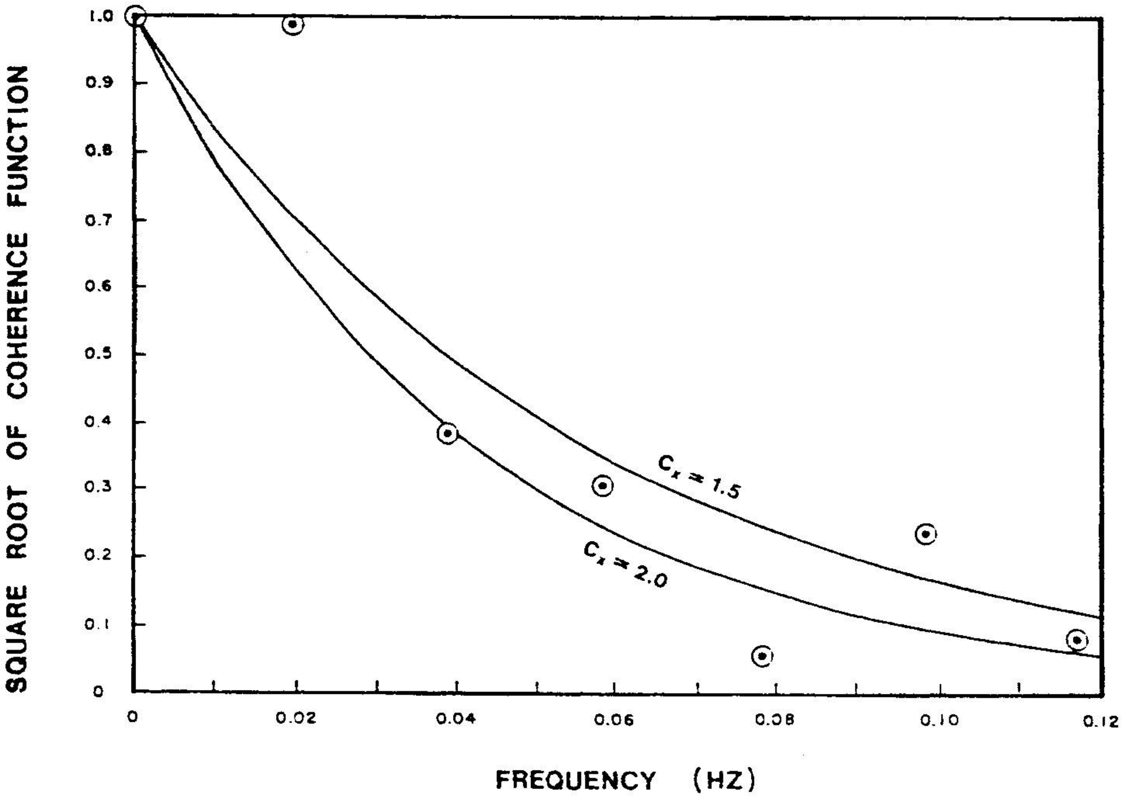

Fig. 9 Coherence of wind turbulence

8. CONCLUSIONS

Systematic measurements have been made of the response of cable stays to vortex shedding and wake induced forces. In addition a first mode response of stays to either galloping or bridge deck motion has been recorded. Both the displacements and stresses from these three sources are small in the range of wind speeds monitored since 1984. First mode vertical and torsional displacements of the main span also have been observed, the vertical displacement arising from a resonant vibration of the deck with vorticies shed from the box girders. Although the onset of this resonance is in accord with predictions from wind tunnel studies, the acceleration and displacement amplitudes are much less than values predicted on the basis of assumptions of bridge damping of one percent of the critical value and coherent vortex shedding along the entire length of the main span. The vertical motion of the deck is transferred by the cable-stays into the principal oscillation observed at the tower tops. Various parameters and spectra characterizing the wind turbulence at the bridge site were measured and found to be within the expected range of values for such data.

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