DYNAMIC PROPERTIES OF SUSPENSION BRIDGES

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Experimental determination of the natural frequencies of vibration, the vertical and torsional mode shapes, and the modal damping of the Newport Bridge, Rhode Island, and the William Preston Lane Memorial Bridge, Maryland, is briefly described. The results of the 2 measurements are compared to show fundamental similarities in their dynamic behavior. The similarities include the order that the types of motion of the deck occur. This order is as follows: symmetric vertical, antisymmetric vertical, antisymmetric vertical, symmetric vertical, symmetric vertical, symmetric torsional, and antisymmetric vertical. The ratios of higher order modal frequencies to the lowest modal frequencies are graphed. The mean ratios on the 2 bridges are found to agree within 10 percent. These factors may serve as useful rules of thumb during the design of suspension bridges.

•THE DYNAMIC behavior of bridge structures has been studied by engineers and scientists for many years. It is safe to say that, while techniques for studying dynamic response of structures have advanced rapidly during the past few decades, we are still a long way from a complete understanding of the behavior of these complex structures.

In developing new analytical techniques to model bridge structures more accurately, we must keep 2 very important points in mind.

1. The engineer seeks to create a mathematical or analytical model to describe a physical entity. Therefore, while advancements can be made following prescribed mathematical guidelines, the validity of the model depends on its verification with reality.
2. Engineering by its very history is a science that is based on experience. Often this means learning from experimental studies. The lessons learned from either full-scale or model studies are invaluable in expanding our experience. Therefore, it is this blend of theoretical development and implementation plus experimental testing that continual improves our method of bridge design.

The digital computer has made dynamic studies of structures economically feasible. Analyses using the natural modes of vibration have been used for simple structures such as high-rise buildings for some time. Similar techniques are now being used for the analysis of more complex structures such as suspension bridges. In high-rise buildings, simple rules of thumb have been developed to aid in determining the reasonableness of the analysis, for example, building period, in sec, 0.1 × number of floors; frame building, $f_n/f_1 = 1, 3, 5, 7$; and cantilever building, $f_n/f_1 = 1, 6.25, 17.5$.

This paper suggests that similar rules may be developed for bridges as more information on their dynamic properties becomes available. This suggestion is supported by summarizing the experimental results obtained during 2 recent full-scale studies to determine the dynamic properties of medium-sized suspension bridges and by showing how a comparison of the results may be used to establish some preliminary rules of thumb for this class of bridge.

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These preliminary guides should be helpful to design engineers during the early stages of a bridge design and serve as a qualitative check on the final design even though data from more bridges must be gathered and evaluated before rules that may be considered universal are developed.

DESCRIPTION OF BRIDGES

The Newport Bridge, which crosses the Narragansett Bay in Rhode Island, and the William Preston Lane Memorial Bridge, which crosses the Chesapeake Bay in Maryland, were studied. The Newport Bridge opened in June 1969. The William Preston Lane Memorial Bridge opened in 1952.

The suspended section of the Newport Bridge is 2,976 ft long, including a 1,600-ft main span, and two 688-ft side spans. The cables are 66 ft apart, and the roadway is 48 ft wide. The towers are 400 ft high. The roadway at the towers is approximately 218 ft above mean water level.

The suspended section of the William Preston Lane Memorial Bridge is 2,920 ft long, including a 1,600-ft main span and two 658-ft side spans. The distance between the cables is 39 ft, and the roadway is 28 ft wide. The towers are 354 ft tall. The roadway at the towers is approximately 194 ft above mean water level.

THE AMBIENT VIBRATION SURVEY

Ambient vibration surveys (AVS) were performed on the 2 suspension bridges in 1969. The details of these surveys can be found in other reports (1, 2, 3).

The main objective of the AVS of these bridges was to measure the natural frequencies and mode shapes of bridge deck vertical and torsional modes. In addition to this primary objective, the surveys also provided estimates of lateral deck natural frequencies of vibration.

The procedure used in the AVS of the bridge was to record on magnetic tape the motion sensed from an array of 7 seismometers. After a period of time, all but one of the seismometers were moved to different locations and data were again recorded. The seismometer that was not moved was used as a reference, and all data were normalized or compared to the reference. Five arrays were used to complete the survey. Figure 1 shows qualitatively the distribution of the seismometers in the arrays.

Traffic was moderate, and winds were generally light during the survey of the Newport Bridge. Traffic was heavy, and the wind varied from calm to strong (approximately 30 mph) during the survey of the William Preston Lane Memorial Bridge.

The recorded data were analyzed by using random vibration theory and power spectral density techniques. Other reports (3, 4, 5, 6) give more details on the statistical methods used to estimate the natural frequencies, modal damping coefficients, and mode shapes.

The analysis included generation of a graph of autopower spectral density of the motion at each instrument location and comparing the motion at each station to the motion at the reference station. The cross-spectral comparison yields graphs of the relative amplitudes and phase angles of the motion at the two points. Examples of the graphs are shown in Figures 2, 3, and 4 respectively. The locations on the bridge represented by the graphs are indicated in the lower left corners.

The damping values given in Tables 1 and 2 were obtained by using the "½ power point" method. The analysis procedure is described elsewhere (3).

BRIDGE CHARACTERISTICS

The dynamic behavior of both bridges included vertical, lateral, and twisting modes of vibration. The measurement plan was designed to obtain detailed information on the vertical and twisting modes only. The analyses were limited to investigation of frequencies less than 1 cycle per second. Table 1 gives the frequencies of vibration identified for the Newport Bridge and Table 2 gives similar information for the Memorial Bridge.

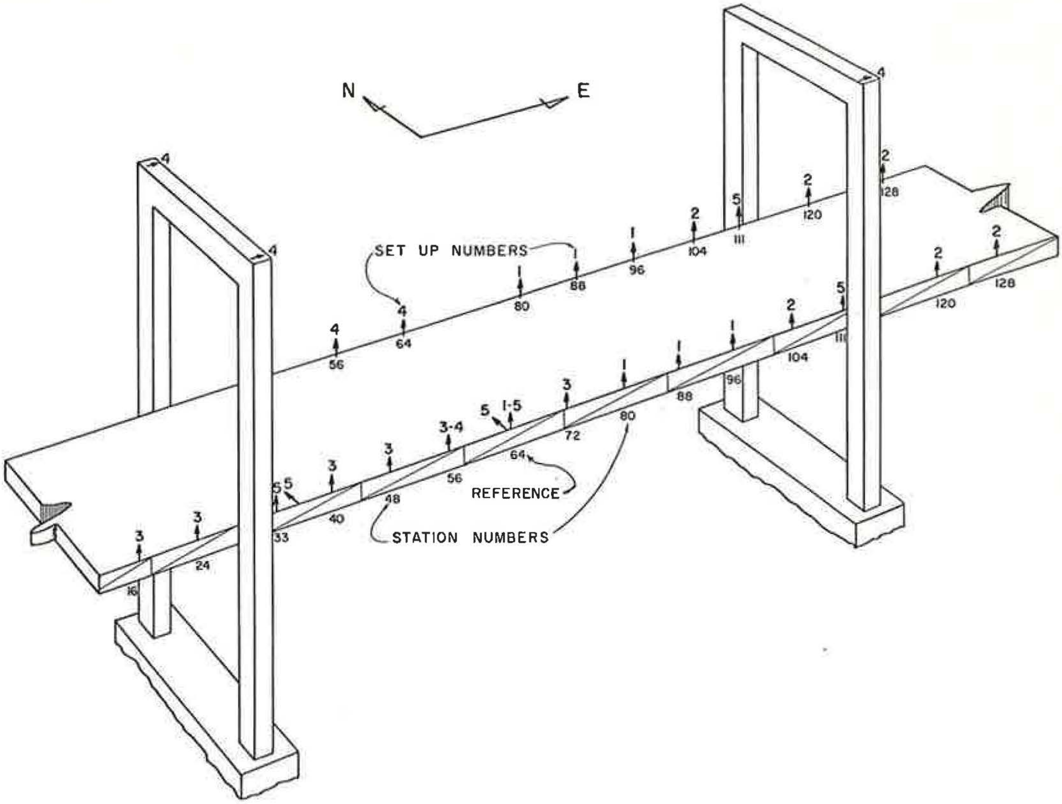


Figure 1. Instrument locations for ambient vibration surveys of bridges.

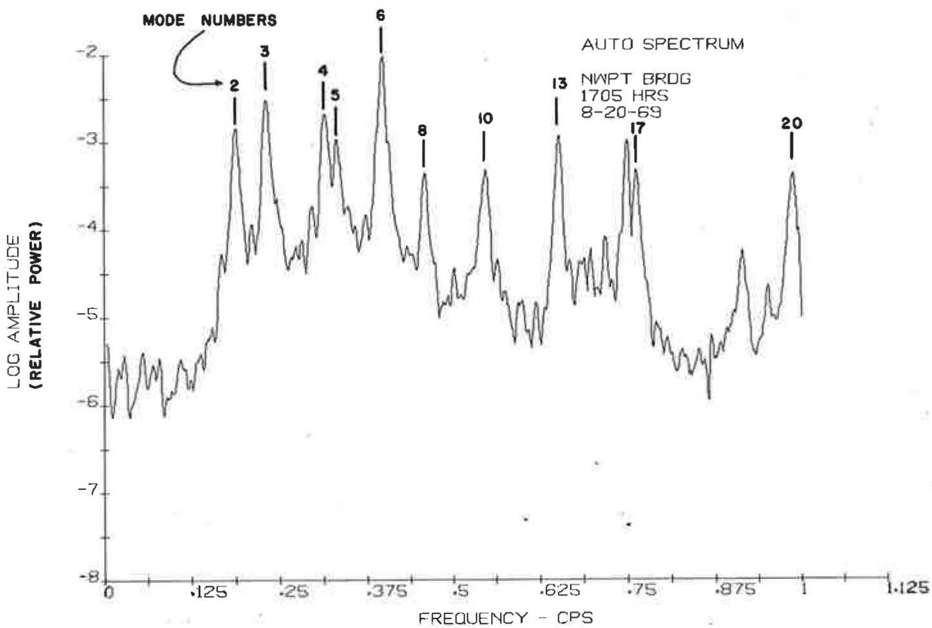


Figure 2. Power spectral density showing frequencies of vibration.

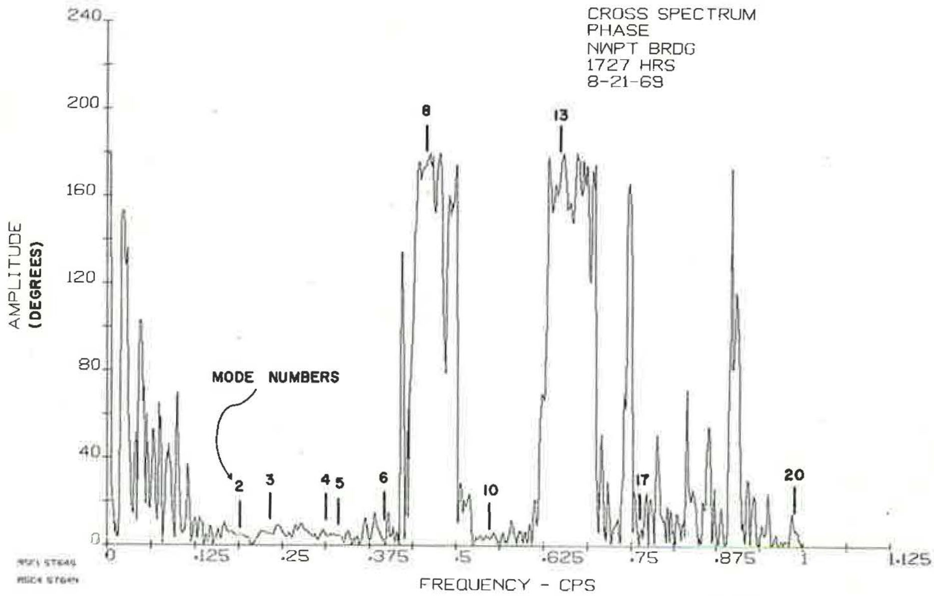


Figure 3. Relative phase angle between 2 seismometer locations.

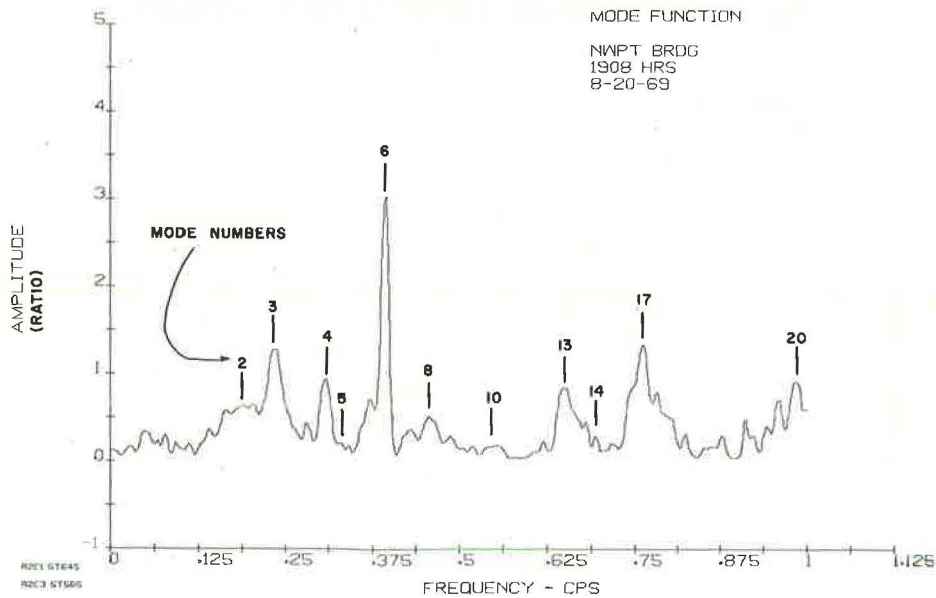


Figure 4. Relative amplitude between 2 seismometer locations.

TABLE 1

SUMMARY OF MODES OF VIBRATION FOR NEWPORT BRIDGE

Mode	Frequency (cpm)	Period (sec)	Damping		Classification
			Percent of Critical Damping	Logarithmic Decrement	
1	9.3	6.45	3.0	0.188	First lateral
2	11.1	5.42	2.0	0.126	First symmetric vertical
3	13.8	4.53	1.7	0.107	First antisymmetric vertical
4	18.7	3.2	2.0	0.126	Second antisymmetric vertical
5	20.0	3.00	1.1	0.069	Second symmetric vertical
6	23.6	2.54	1.1	0.069	Third symmetric vertical
7	25.2	2.38	1.1	0.069	Second lateral
8	27.3	2.20	0.8	0.050	First symmetric torsional
9	31.2	1.92	1.2	0.075	Third lateral
10	32.5	1.85	0.9	0.056	Third antisymmetric vertical
11	37.2	1.62	0.6	0.038	First longitudinal tower
12	38.4	1.56	0.5	0.031	Fourth lateral
13	39.0	1.54	0.8	0.051	First antisymmetric torsional
14	41.3	1.45	0.6	0.038	Fourth symmetric vertical (side spans)
15	42.3	1.42	0.6	0.038	Fifth lateral
16	44.8	1.34	0.5	0.031	Second longitudinal tower
17	45.3	1.32	0.8	0.050	Fifth symmetric vertical
18	48.4	1.24	0.8	0.050	Third longitudinal tower
19	49.2	1.22	0.9	0.056	Sixth lateral
20	59.6	1.006	0.4	0.025	Fourth antisymmetric vertical

TABLE 2

SUMMARY OF MODES OF VIBRATION FOR WILLIAM PRESTON LANE MEMORIAL BRIDGE

Mode	Frequency (cpm)	Period (sec)	Damping		Classification
			Percent of Critical Damping	Logarithmic Decrement	
1	6.3	9.52	5.4	0.339	First lateral
2	12.3	4.88	2.5	0.157	First symmetric vertical
3	15.6	3.85	2.2	0.138	First antisymmetric vertical
4	19.2	3.13	1.4	0.088	Second lateral
5	21.0	2.86	1.4	0.088	Second antisymmetric vertical
6	24.9	2.41	1.1	0.069	Second symmetric vertical
7	28.8	2.08	1.6	0.100	Third symmetric vertical
8	35.1	1.71	0.5	0.031	Third lateral
9	37.7	1.59	1.3	0.082	Fourth lateral
10	40.5	1.481	1.4	0.088	First symmetric torsional
11	44.4	1.351	0.9	0.057	Third antisymmetric vertical
12	51.9	1.16	0.9	0.057	Fifth lateral
13	55.9	1.07	0.4	0.025	Sixth lateral

In other reports (1, 2, 3), the mode shapes were drawn for each of the vertical and twisting modes of the decks. In order to assist in the physical understanding of the modal response of the bridges, Figure 5 shows the first symmetrical vertical and torsional mode shapes of the Newport Bridge. Figure 6 shows the first and third antisymmetrical vertical mode shapes of the Memorial Bridge.

COMPARISON OF RESULTS

Each bridge's vertical mode dynamic characteristics is presented in a form conducive to a comparative study of the 2 bridges. While such a comparison can be supported by using similarities in each bridge's ratio of center span length to side span length, it should be noted that the opening dates of these bridges were separated by nearly 20 years. Therefore, the main purpose of this section is to show the surprising similarity of the dynamic characteristics of these bridges in some important aspects.

Figures 7 and 8 show the first 7 vertical and torsional deck natural frequencies and mode shapes for the Newport Bridge and the Memorial Bridge respectively. The right

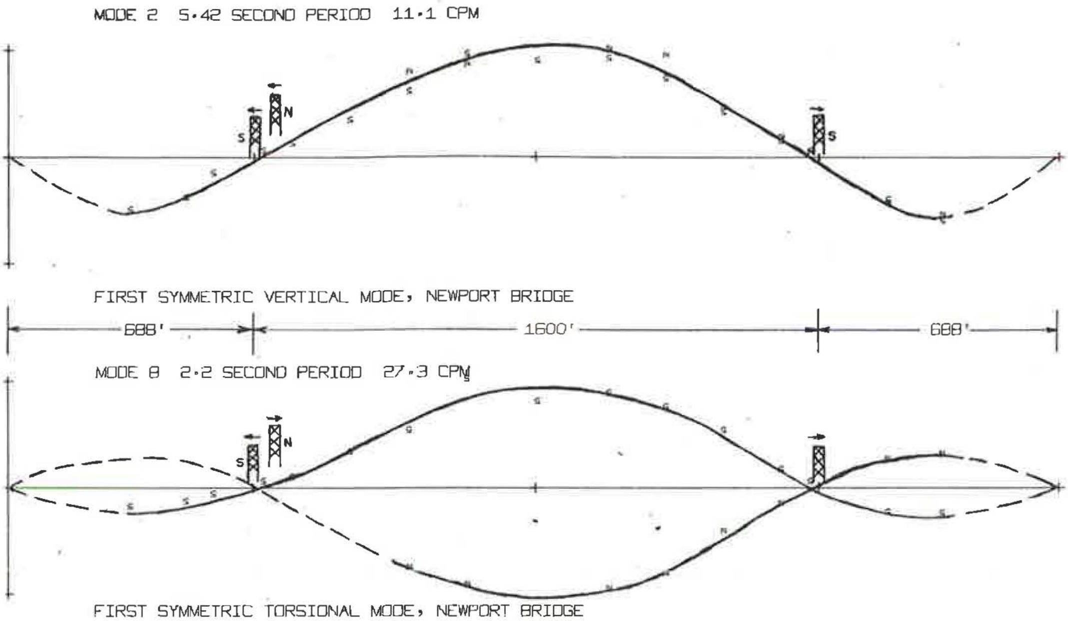


Figure 5. Symmetrical mode shapes of Newport Bridge.

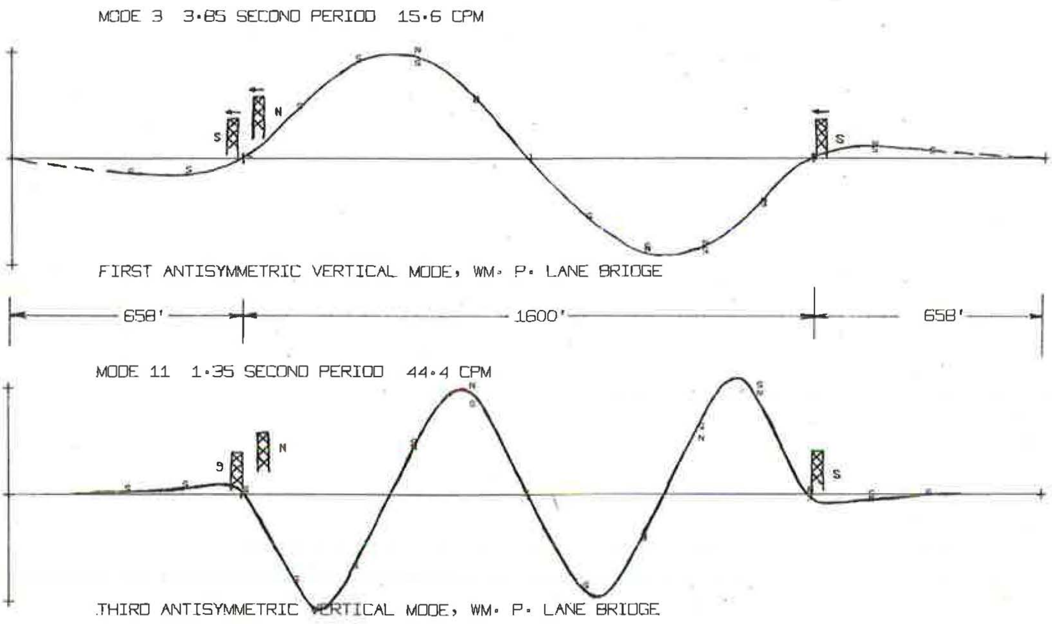
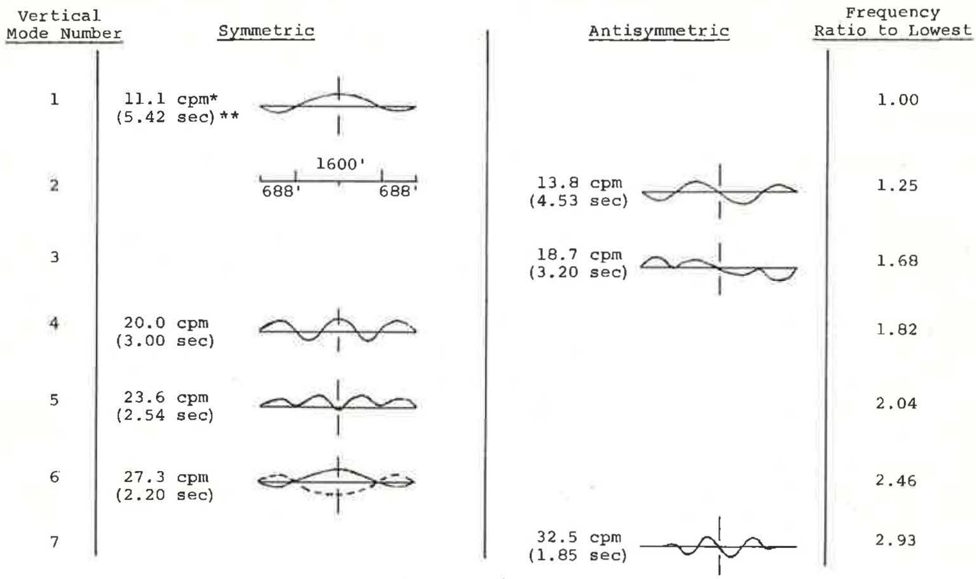


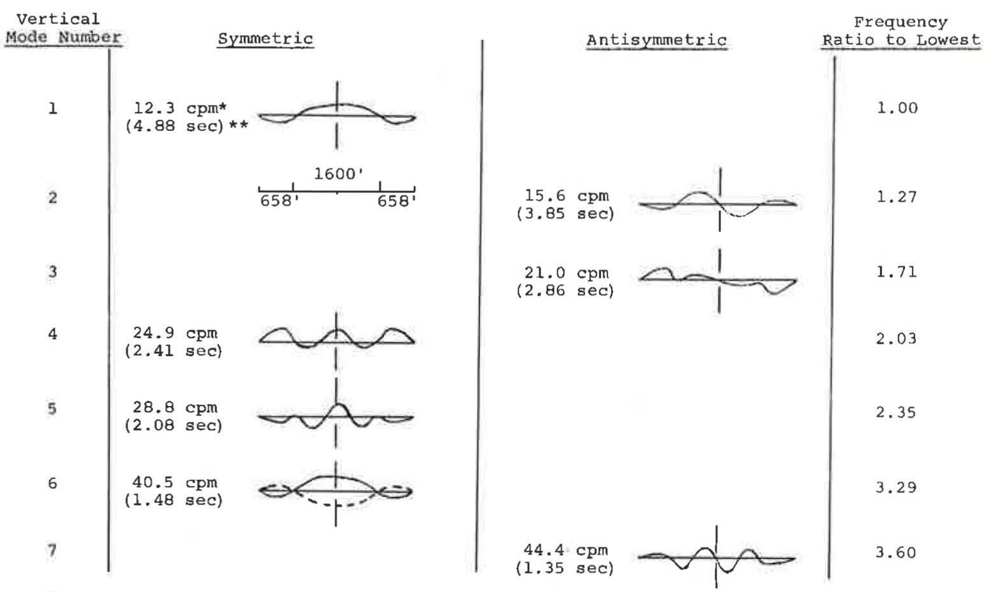
Figure 6. Antisymmetrical mode shapes of William Preston Lane Memorial Bridge.



* Normal mode natural frequency in cycles/minute
(center span length/side span length) - 2.34

** Period of mode

Figure 7. Vertical mode shapes and natural frequencies of Newport Bridge.



* Normal mode natural frequency in cycles/minute
(center span length/side span length) = 2.43

** Period of mode

Figure 8. Vertical mode shapes and natural frequencies of William Preston Lane Memorial Bridge.

column in each figure gives the ratio between the higher mode natural frequencies and the fundamental vertical natural frequency. These ratios are shown graphically in Figure 9a. The ratio between the higher symmetric and antisymmetric vertical frequencies and the lowest natural frequency in each of these categories is shown in Figure 9b and c.

A careful study of Figures 7, 8, and 9 shows the following:

1. Each bridge possesses the same sequencing of symmetric vertical, S; antisymmetric vertical, AS; and symmetric torsional, ST, mode shapes. This sequence is S, AS, AS, S, S, ST, and AS.

2. Figure 9a shows that the ratio between the higher order natural frequencies and the fundamental vertical natural frequency was nearly constant for both bridges. If the estimated mean (or average) ratios between the higher order and the fundamental vertical natural frequencies of 1.25, 1.70, 1.90, 2.20, 2.88, and 3.25 are used, then the percentage differences between these values and any one of those calculated are a minimum of 1.2 percent (third mode) and a maximum of 10.7 percent (seventh mode).

3. The ratio between each higher symmetric vertical frequency and the lowest symmetric vertical frequency is shown in Figure 9b. If mean ratio estimates of 1.90 and 2.20 are used, then these ratios differ from the original by 6.8 and 8.2 percent respectively. For the antisymmetric vertical frequencies, the corresponding mean ratios are 1.35 and 2.60. The percentage differences in these cases are 0.0 and 9.6 percent respectively.

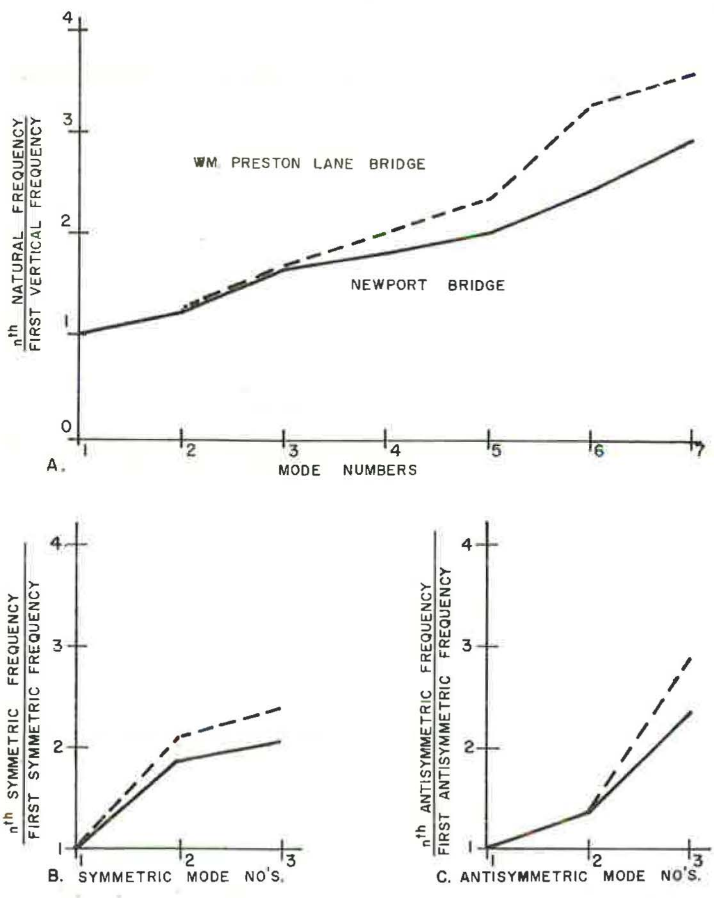


Figure 9. Frequency ratios.

These observations provide helpful insight into frequency ratios for these 2 bridges. While these bridges differ in many aspects, it is clear that common general trends exist in their frequency ratios. To be sure, these vertical frequency ratios reflect the fact that each bridge deck behaved to a fair degree of approximation like a multiple-span, simply supported, continuous beam.

The previous paragraphs of this section provide a qualitative basis for the assumption that the gross behavioral characteristics of bridges can, to a fair degree of accuracy, be placed into categories. Of course, for the final design of a bridge, natural frequencies should be obtained by using state-of-art analysis techniques. However, experimentally obtained guidelines such as these will help in preliminary design and analysis verification phases of a project.

ACKNOWLEDGMENT

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