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NATURAL FREQUENCY OF TRAFFIC FLOW-BRIDGE SYSTEM BASED ON CELLULAR AUTOMATON TECHNIQUE

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Abstract. *Based on Cellular automation (CA) traffic flow simulation technology widely used in the transportation field, a general framework of investigating the variation of natural frequencies of a roadway bridge under vehicle flow was developed. The results revealed that the values of the frequencies decrease as the traffic density increases and the effect on high modes of the bridge under vehicle flow is more significant.*

1 INTRODUCTION

Research on the dynamic behavior of bridges under moving vehicle loads can be dated back to many years ago, especially for railway bridges [1-8]. There are numerous publications regarding the dynamic analysis of train-bridge interactions [1-5]. Some of them focused on the effect of trains on the natural frequencies of bridges due to the effects of carriage masses coupled with the bridges through suspension systems, namely railway bridge on-load natural frequency. Ren et al. [7] focused on continuous bridges and some results showed that the vertical train-bridge natural frequency periodically varied when the trains were distributing on the whole bridge. Recently, the significance and the variation trend of driving frequencies and dominant frequencies in the response arising from the trainload was examined by Lu et al [6].

In recently year, there have been an increasing number of problems related to highway bridges. One of the problems is that the natural frequencies of the bridges decrease. As a result, it was desirable that the frequencies variation of bridge under traffic flow should be considered. Based on traffic-induced vibration tests on three bridges, the measured natural frequencies can change up to 5.4% for the short span bridges whose mass is relatively small [9]. The interaction between vehicular traffic and bridge vibration for a short span bridge was studied experimentally and analytically by Kwon et al [10]. The relative and absolute frequency changes of damaged reinforced concrete bridge structures under moving vehicular loads are sensitive to the weight of the moving vehicle, and the frequency ratio between the vehicle and bridge has some effect on them [11]. A theoretical framework is presented for the variation in frequencies of vibration of the VBI system by Yang et al [12-14], which indicated that the effect will be crucial when the vehicle mass is not negligible compared with the bridge mass or when the resonance condition is approached.

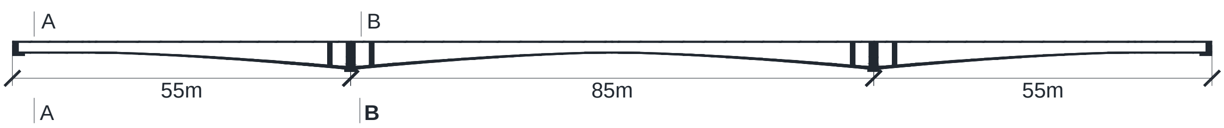
Some theoretical studies above are related to bridge on-load natural frequencies. For a train-bridge system [6-8], the train is modelled as multiple carriages and the bridge is modeled as a beam. For studying a vehicle-bridge system, similar to that of a train-bridge system, the vehicle is modeled as a moving mass [14] or a several degrees-of-freedom system [10-13] and the bridge is modeled as a beam. However, the vehicle-bridge system is much different from the train-bridges system such as load distribution and mechanical characteristics. Therefore, the model of vehicle-bridge system mentioned above can capture the physical essence of roadway bridge on-load natural frequencies. It is impossible to be applied to the real bridge.

This study aims to present a method to investigate the variation of natural frequencies of a roadway bridge under vehicle flow and various tasks are provide in several sections.

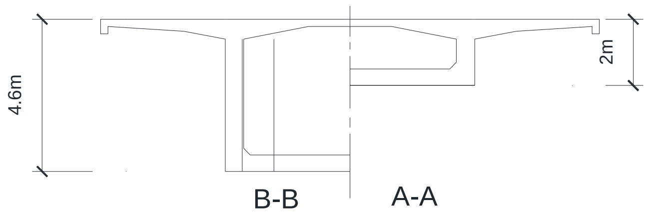
2 FEM BRIDGE MODEL

The case study is a continue box-girder bridge. The bridge has three spans, namely 55m+85m+55m, with a total length of 195 m. The width of the bridge is 15m. A scheme of the bridge is shown in Fig. 1. ANSYS was used to construct a full 3-D FEM of the bridge.

The bridge has been considered composed by three different materials for different structural elements: the box-girder (steel reinforced concrete), the pavement of the bridge (bituminous concrete), bridge supports (rubber bearing), with the characteristics reported in Table 1. The damping and nonlinear properties of the bridge are not considered in this study.



(a) Elevation



(b) Typical cross sections
Fig. 1. A scheme of the bridge (units: m).

Solid elements are used to build the model as shown in Fig.2. There are a total of 26,296 elements and 50,459 nodes. The first four natural frequencies of the bridge were determined using Block Lanczos method and presented in Table 2 respectively.

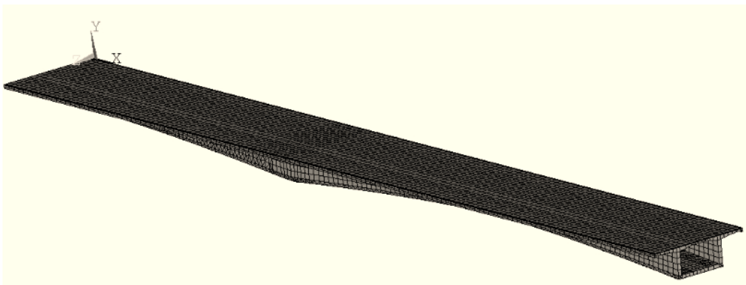


Fig. 2. A FE model of the bridge (a half)

Table 1. Mechanical Characteristics

Material	Steel reinforced concrete	Bituminous concrete	Rubber bearing
Young Modulus (N/m^2)	3.7e10	4.5e9	3.7e8
Density (kg/m^3)	2500	2440	2150
Poisson ratio	0.2	0.4	0.4

Table 2. Natural frequency for the first six modes

Mode No.	1	2	3	4
Natural frequency (Hz)	1.069	1.862	2.245	2.638

3 STOCHASTIC TRAFFIC FLOW ON A ROADWAY BRIDGE

Cellular automaton (CA) traffic flow simulation technology [16-18] is adopted to develop the stochastic traffic flow. The method is able to provide detailed instantaneous information of each vehicle through replicating major traffic phenomena on roadways. Thus it is an ideal technology to be integrated into the advanced bridge analysis considering traffic flow in a more realistic manner.

3.1 Theoretical basis

CA traffic model is to simulate the stochastic traffic flow through discrete time and space and each lane is divided into cells with an equal length. Each cell can be either empty or occupied by one vehicle at a time. At each time step, a vehicle moves, accelerates, decelerates or changes lanes based on some predefined rules [16-18]. The rules of a typical CA traffic model include: (1) the rules of the single-lane CA model; and (2) the conditions for lane changing. Vehicle i is taken as an example to introduce the CA traffic model rules. $v_i(t)$ and $v_i(t+1)$ are the velocities at time t and $t+1$ respectively. $L_i(t)$ and $L_{i+1}(t)$ denote the locations of vehicle i and the vehicle immediately ahead of vehicle i. $v_{\max}$ represents the maximum velocity. $\mathbf{gap}_i(t)$ is the distance between vehicle i and vehicle $i+1$. ρb denotes the randomization probability.

The rules for the single-lane CA model are shown as follows:

Rule 1: acceleration, $v_i(t+1) = v_i(t)+1$ if $v_i(t) < v_{\max}$ and $\mathbf{gap}_i(t) > v_i(t)+1$.

Rule 2: deceleration, $v_i(t+1) = \mathbf{gap}_i(t)-1$ if $\mathbf{gap}_i(t) <= v_i(t)+1$.

Rule 3: randomization, $P(v_i(t+1) = v_i(t)-1) \mid v_i(t) > 0) = \rho b$.

Rule 4: vehicle motion. If the three conditions above are not satisfied, then $v_i(t+1) = v_i(t)$.

Vehicle i will change to the target lane with the probability of ρch if all the three following criteria are satisfied:

Rule 5: $\mathbf{gap}_i(t) <= v_i(t)+1$.

Rule 6: $\mathbf{gapo}_i(t) > v_i(t)+1$, $\mathbf{gapo}_i(t) = L_{f,i}(t) - L_i(t)$, $L_{f,i}(t)$ denote the location of the nearest vehicle on the target lane moving ahead of vehicle i.

Rule 7: $\mathbf{gapoback}_i(t) > v_{\max}$, $\mathbf{gapoback}_i(t) = L_i(t) - L_{b,i}(t)$, $L_{b,i}(t)$ is the location of the nearest vehicle on the target lane moving behind vehicle i.

To complete a lane-changing simulation, the location and the velocity of vehicle i will be updated through two sub-steps:

Step 1: vehicle i moves to the target lane transversely without moving forward.

Step 2: vehicle i moves forward obeying the single lane rule as illustrated above after moving into the target lane.

3.2 Traffic flow simulation on the bridge

In the present study, the bridge is a two-lane one-way bridge and a steel reinforced concrete bridge. Actually, frequencies variation of the bridge under vehicle flow is not obviously, because the vehicle mass is small compared with the bridge mass. Even though, it is sufficient to interpret the method suggested in the paper to analysis the natural frequencies of a roadway bridge under vehicle flow.

The total length of the bridge is 195 m (L_b). Chen et al.[18] suggested that approaching roadways on both sides of the bridge should be considered, because the actual traffic flow through a bridge is also affected by the traffic on the approaching roadways. The approaching roadway has the length of 975 m (L_r) at each end of the bridge in the present study [18]. The length of 'roadway-bridge-roadway' system is 2145m. The bridge and the approaching roadways have the same number of available lanes. All the lanes on the bridge and the connecting roadways share the same width and each lane is divided into equally-spaced cells. The rules of the bridge and the approaching roadways are the same. The length of each cell (L_c) is set to be 7.5 m [18], which is the typical distance between the centers of two vehicles when the road is in a complete congestion. Then, the number of all cells in one lane is 286 (N).The velocity limit $V_{\max}$ is assumed to be 120 km/h, which is the typical speed limit on highways in China. The period of each time step is 1s. So $v_{\max}$ in the CA model can be computed accordingly:

$$v_{\max} = \frac{V_{\max}}{L_c} = \frac{120(\mathbf{km/h})}{7.5(\mathbf{m/cell})} = 4.44(\mathbf{cell/s}) \approx 4(\mathbf{cell/s}) \quad (1)$$

In the following CA-based traffic flow simulation, the periodic boundary condition is adopted. The initial velocities of all the vehicles are randomly set among $0 \sim 4$(**cell/s**). The CA traffic simulation rules will decide the velocity of each individual vehicle according to the speed limit adaptively. The probability of braking (ρb) is 0.5. The probability of changing lane (ρch) is 0.8. Various vehicles on highways are grouped into eight categories, the weights of various vehicles are summarized in Table 2. The proportions of the vehicles in each category are assumed to be 0.125 equally.

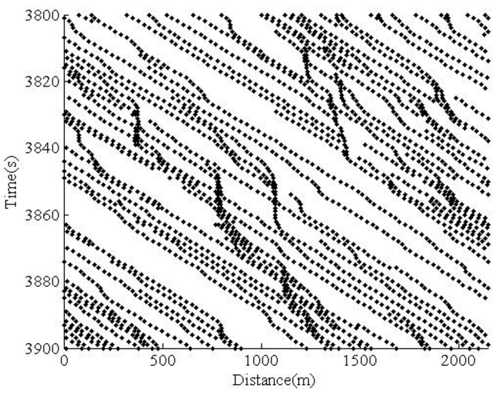
Table 2. The weight of various vehicles

Categories	car	Mini bus	Light bus	bus	Mini truck	Light truck	Truck	Heavy truck
Weight (kg)	2000	7220	10000	20000	10000	15000	25000	32000

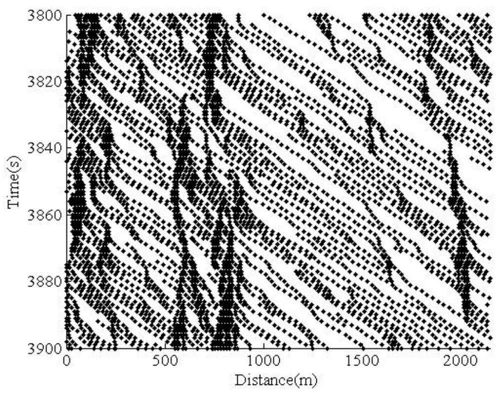
With the adoption of the periodic boundary condition, the traffic occupancy in the whole system keeps constant for each simulation. Four densities (ρ) are considered in the present study: (1) $\rho = 0.08$ (11 veh/km/lane), (2) $\rho = 0.16$ (22 veh/km/lane), (3) $\rho = 0.24$ (32 veh/km/lane), (4) $\rho = 0.36$ (50 veh/km/lane). The first three densities (1), (2), (3) correspond to Level of service of B, D, F respectively. The last density (4) are proposed for this research. The observation of the traffic flow will start after $t_0 = 10C$ (C is the number of all cells in one lane, here $C = 286$) when the traffic flow is typically believed to become steady [18]. Thus, the traffic flow starting from 3000 s in this study will be presented in the following sections.

The typical two-lane traffic simulation of a 'roadway-bridge-roadway' system is conducted and the results are shown in Fig. 3. As presented in Fig. 3, the time versus space information of the simulated traffic flow on one lane is given. The x-axis shows the physical location of each vehicle on the 'roadway-bridge-roadway'. The y-axis shows the time range after 3000 s of simulation elapsed. At any time instant on the y-axis, the information of the physical distribution of each vehicle along the spatial simulation region (x-axis) can be found by drawing a line horizontally. Similarly, at any spatial location on the x-axis, the time-variant information of vehicles at one particular location can also be retrieved by drawing a line vertically.

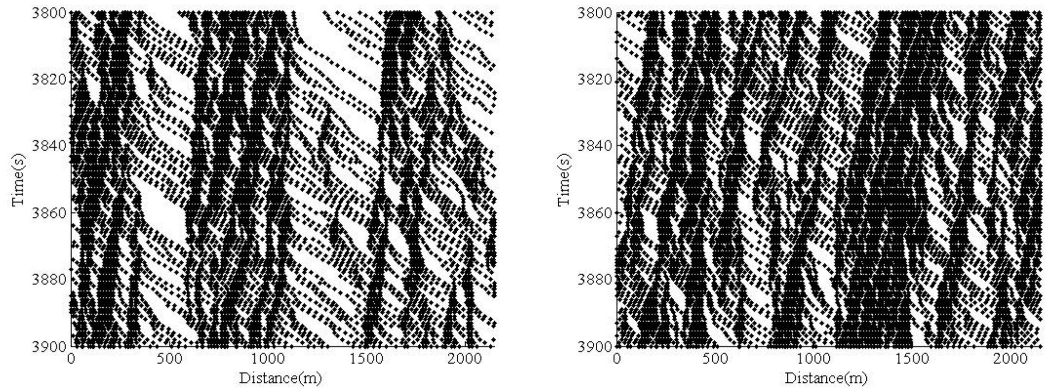
In Fig. 4, we show four different situations at four different densities. Operational condition of the bridge is free flow at $\rho = 0.08$. As the density increase, traffic congestion appears. The ability to maneuver is severely restricted due to traffic congestion at $\rho = 0.16$. At $\rho = 0.24$ and $\rho = 0.36$, the traffic flow breakdown. Vehicles arrive at a rate greater than the rate at which they are discharged. Operations within queues are highly unstable, vehicles experiencing brief periods of movement followed by stoppages.



(a) $\rho = 0.08$



(b) $\rho = 0.16$



(c) $\rho = 0.24$ (d) $\rho = 0.36$

Fig. 3. Traffic flow simulation result

4 TIME-VARIANT NATURAL FREQUENCIES OF BRIDGE

The FE model of the bridge and traffic flow on the bridge have been obtained above. Each vehicle in the stochastic traffic flow is modeled as a mass, it is convenient to determine time variant natural frequencies of bridge under traffic flow. The weights of various vehicles are presented in Table 2. The following is the procedure used to determine time variant natural frequencies of bridge under vehicle flow.

Step 1: Establish FE model of the bridge in ANSYS.

Step 2: Simulate traffic flow cross the bridge based on Cellular automaton (CA) traffic flow simulation technology.

Step 3: Obtain positions of all vehicles distributed on the bridge at time step t from traffic flow simulation result.

Step4: Establish the FE models of all vehicles on the FEmodel of bridge according to the position of vehicle and vehicle type. MASS 21 is adopted to simulate the vehicle.

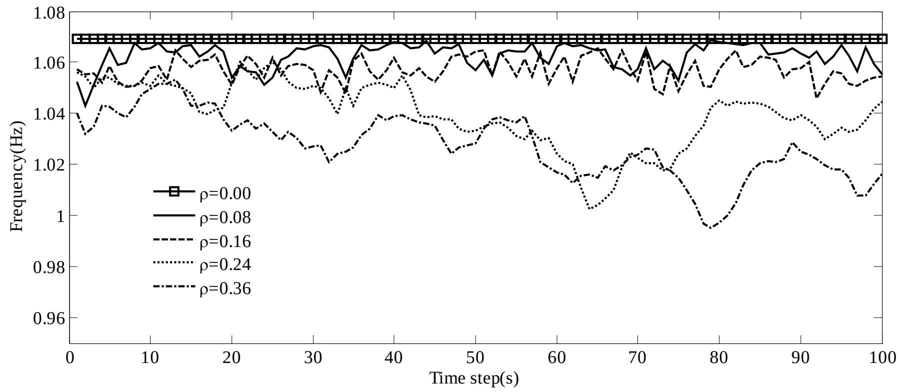
Step5: Calculate the frequency of traffic flow-bridge system at time step t.

Step6: Check the traffic flow. If the traffic flow has crossed the bridge, the time variant natural frequencies of bridge under traffic flow is finish.

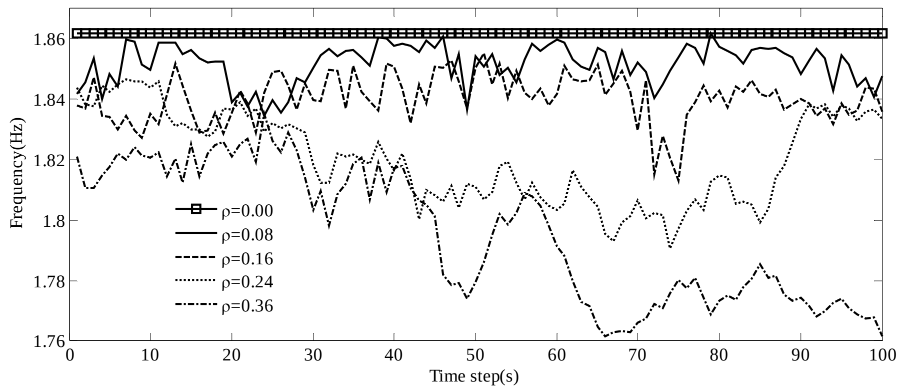
Step7: At time step $t+1$, go to step 3 and repeat the procedure until the traffic flow has crossed the bridge.

Due to the traffic flow through the bridge, the natural frequencies of the bridge at any one moment is usually different from that at the next moment. The variations of the first four frequencies with time as the vehicles pass over bridge are shown in Fig.4. Legend $\rho = 0.00$ represents that there are no vehicles on the bridge. Compared to the natural frequencies of bridge ($\rho = 0.00$), the frequencies of bridge under vehicle flow decrease at any time instant. From Fig. 4, as the traffic density increase, the natural frequencies decrease in general. Larger fluctuations of the natural frequencies under traffic flow over time are observed in Fig.5 when the traffic density is high.

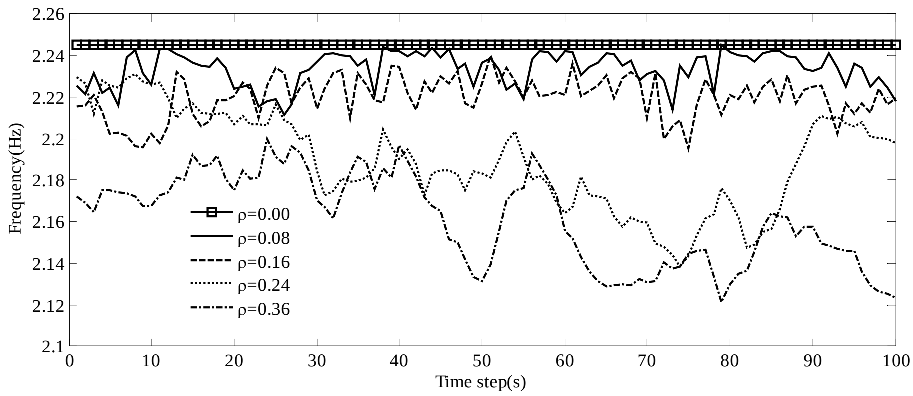
In order to investigate the effect of the vehicles on different mode of bridge under vehicle flow, the time-history of difference between natural frequencies of the bridge and the bridge with vehicle for the four traffic densities are shown in Fig.5 (a)-(d), respectively. From Fig.6, it can be concluded that the effect of the vehicles on the higher modes of the bridge under vehicle flow are more significant than on the lower modes in general.



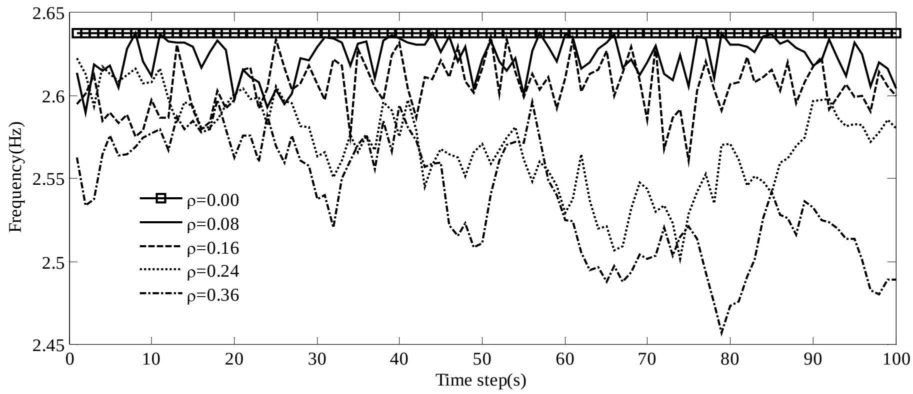
(a) 1st natural frequency



(b) 2nd natural frequency

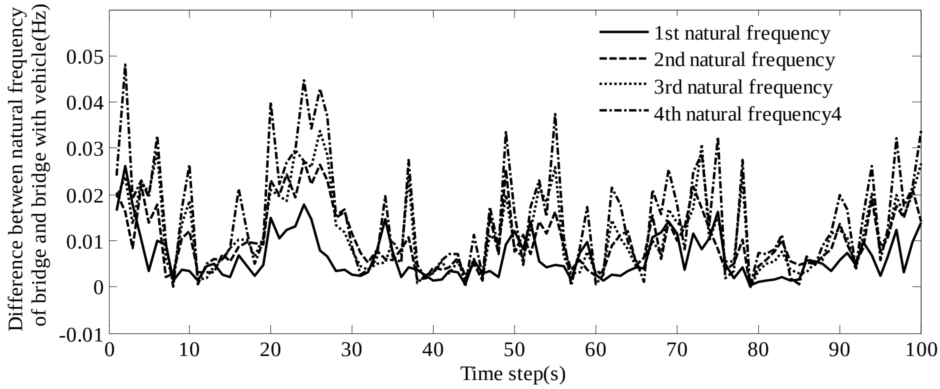


(c) 3rd natural frequency

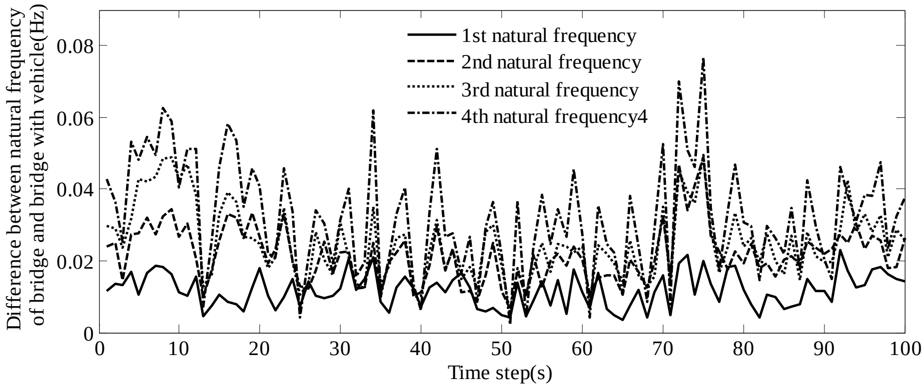


(d) 4th natural frequency

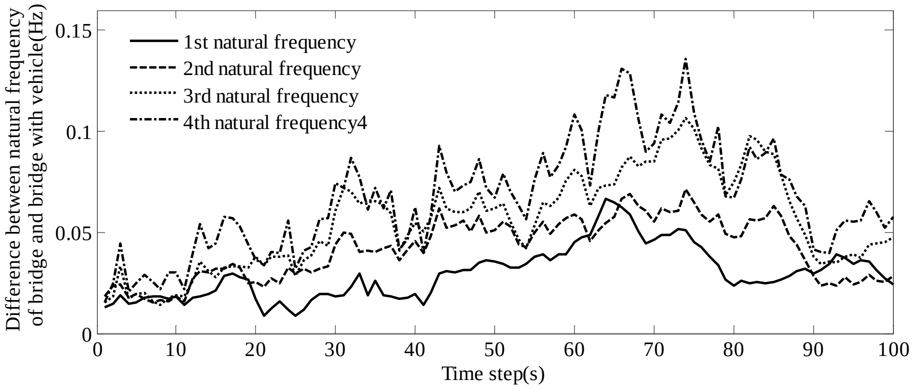
Fig. 4. The variations of the first four frequencies with time as the vehicles pass over bridge



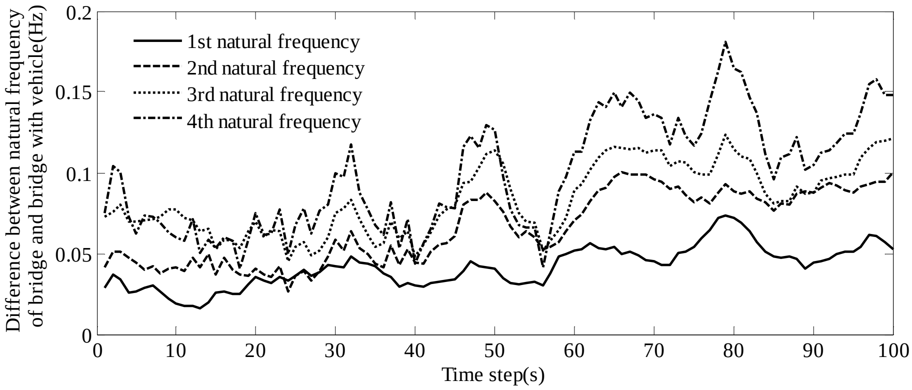
(a) $\rho = 0.08$



(b) $\rho = 0.16$



(c) $\rho = 0.24$



(d) $\rho = 0.36$

Fig. 5. Effect of the vehicles on different mode of bridge under vehicle flow

5 CONCLUTION

Based on traffic flow simulation technology, a general framework of investigating the variation of natural frequencies of a roadway bridge under vehicle flow was developed. The obtained results revealed that the natural frequencies decrease in general as the value of the traffic density increase. Compared to the natural frequencies of the empty bridge, the natural frequencies of bridge under vehicle flow decrease at any time instant. Moreover, it was shown that the effect of the vehicles on high modes of the bridge under vehicle flow is more significant. The method presented can be used in practical engineering.

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