Experimental study for the effect of hard coating on nonlinear vibration behavior of cantilever thin plate

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Abstract: The nonlinear vibration behaviors of the cantilever hard-coating plate under transverse loading are investigated through vibration response tests. In order to analyze the effects of hard coating on vibration behavior of plates, the comparison test is conducted between cantilever titanium alloy plate and cantilever hard-coating plate under transverse harmonic base excitation, and the test results indicate that NiCrAlY coating exhibits excellent damping performance.

Keywords: hard-coating plate; vibration behavior; damping performance

1 Introduction

As a typical coat material, NiCrAlY exhibits good mechanical properties and superior oxidation resistance [1]. Due to its excellent performances, the NiCrAlY coating prepared by atmospheric plasma spraying, often acts as a bond coat for the thermal barrier coatings in order to extend the life of structural elements. The hard coating plates, which are composed of metal substrate and anisotropic coating, have been broadly used in most of industrial applications, such as aerospace and nuclear power industries. For the safe use and reliable design of the structural element, the

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nonlinear vibration behavior of hard coating plate is essential to experimentally studied [2, 3].

For the metallic rectangular plates, many experts [4-7] conducted experimental investigations on the nonlinear vibration behavior and various nonlinear phenomena have been observed. Considering uniform-distributed periodic loading, Yamaki [8, 9] investigated the nonlinear vibrations of a clamped rectangular plate with initial deflection and edge displacement, and found the experimental result and analytical solution of symmetric periodic response have a good agreement. The large-amplitude forced vibrations of rectangular stainless-steel thin plate was studied by Amabili [10] considering different concentrated masses, the boundary condition was similar to four edges fixed rectangular plate, and the experimental results indicated damping increases nonlinearly with vibration amplitude. Through wind tunnel experiments, Purohit [11] investigated flow-induced vibration of a harmonically actuated flexible plate, and found that the dynamics of flexible plate is influenced by both the flow-induced excitation and external harmonic excitation. Navazi [12] presented an experimental measurement method for energy density of high frequency vibrations of a plate, and the measurement results of both kinetic and potential energy density showed a good agreement with energy finite element analysis.

Some research indicated that damping properties of coatings relate to the microstructure, which is characterized by heterogeneous sets of elastic elements with mesoscopic sizes and shapes, as in non-linear mesoscopic elastic materials. Tassini [13] implemented a phenomenological model that characterizes elastic properties of coatings, and observed damping behavior for zirconia coatings prepared by air plasma spraying and electron-beam physical-vapor-deposition. Zhu [14] developed a high temperature damping test apparatus to determine the damping performance of metallic and ceramic protective coating systems at high temperature, and presented the microstructure and processing effects on the coating temperature-dependence damping behavior.

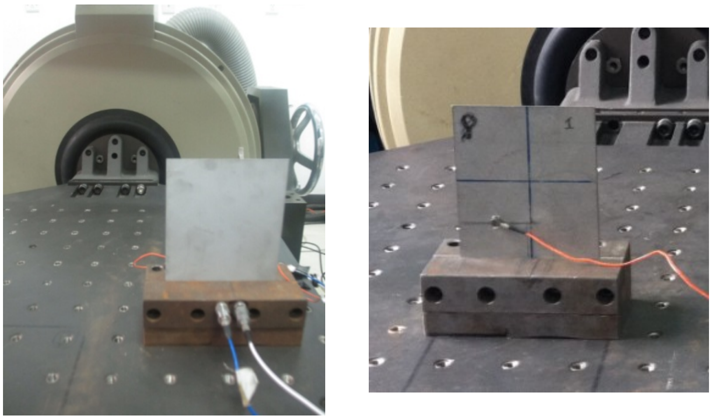
Some researchers experimentally investigated the dynamic behavior of composite plates from another point of view. Considering harmonic excitation, Oh [15, 16] studied dynamic behavior of a cantilever composite plate, and observed high-frequency to low-frequency modal interactions which are similar to elastic beam. Backwell [17] performed the characterization test of titanium plates with hard-coating

($MgO+Al_2O_3$), and obtained the damping of the coated and uncoated specimens in a cantilevered boundary condition, the test indicated the hard-coating increased damping nonlinearly for the modes tested. For the rectangular carbon-fiber-reinforced plastic (CFRP) plate, Lee [18] studied the effect of carbon fiber orientation on its natural vibration mode, and presented the natural frequencies and vibration modes change is due to the stiffness change of CFRP plate caused by the change of carbon fiber orientation. Antonio [19] proposed active vibration control of a free-edge rectangular sandwich plate, and experimentally realized the reducing vibration in linear and nonlinear vibrations regimes and the effective control of each resonance both individually or simultaneously.

In this paper, the nonlinear vibration behaviors of the cantilever hard-coating plate under transverse loading are presented by experimental investigation. In order to study the effects of hard coating on vibration behavior of plates, the comparison test analysis is conducted between cantilever titanium alloy plate and cantilever hard-coating plate under transverse harmonic base excitation. The influences of excitation frequencies on vibration response and frequency spectrum in the nonresonance intervals are obtained. The damping performance of hard coating is obtained, and the results show that the hard coating is able to reduce chaotic motion, especially in high frequency spectrum.

2 Experimental test

To analyze the influence rule of hard-coating on titanium alloy plate, the vibration response tests of titanium alloy plate and hard-coating plate are conducted respectively. The experimental setup is shown as in Fig. 2. The cantilever hard-coating plate and titanium alloy plate are vertically mounted, and a 2200-lb shaker provides an external (i.e., transverse to the plane of the plate) harmonic excitation at the fixed edge of the plate. The dimensions of plates are both 122mm×110mm×1.5mm, and the hard-coating plate is covered by a 15 μm thick NiCrAlY coating. The shaker excitation and the response of the cantilever plate are measured using B&K4517 light accelerometers.



(a) The hard-coating plate (b) The titanium alloy plate

Fig. 2 Experimental setup of vibration response tests

The natural frequencies of titanium alloy plate and hard-coating plate are obtained by a sweep test, and shown in Table 1. The signals of accelerometers are monitored in time domains by a LMS digital signal analyzer. Then, the time- and frequency-response data are stored for further characterization and processing.

Tab. 1. Natural frequencies of titanium alloy plate and hard-coating plate /Hz

Mode	1	2	3	4	5	6	7	8
titanium alloy plate	85.7	227.9	538.2	776	811.6	1443.7	1494.2	1765.2
hard-coating plate	87.7	227.7	538	777.2	814	1463.2	1526	1772.2

3 Vibration behavior test of plates

Frequency-response curves illustrate various characteristics of a nonlinear system like the presence of multiple stable responses, bifurcations, chaotic motion, etc. Therefore, through comparing and analyzing the frequency-response curves of titanium alloy plate and hard-coating plate, the effects of hard coating on vibration behavior of plates are studied.

Under the 1 g ($g = 9.8$ m/s^2) constant excitation amplitude, a sweep from 30 Hz to 2200 Hz is proceeded at the speed of 0.4 Hz/s. By distinguishing the vibration behavior differences of plates, the frequency is divided into different spectra.

3.1 Vibration response characteristics of titanium alloy plate

According to the real-time measured response of titanium alloy plate, excitation frequency can be divided into several frequency spectra as shown in Fig. 3.

Under low frequency, that Ω=30~190Hz, the vibration response of titanium alloy plate manifests multi-periodic motion, and the frequency spectrum includes excitation frequency, the 6th and the 7th order natural frequencies, as shown in Fig. 3(a) and 3(b).

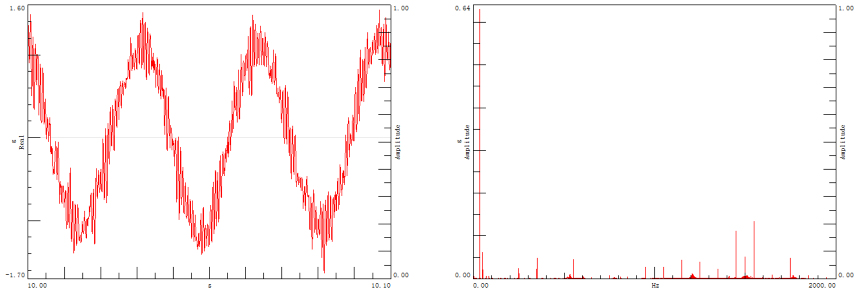
At Ω=210~439Hz, the vibration response manifests quadruple periodic motion, and the frequency spectrum includes excitation frequency, the 3rd, the 6th and the 7th order natural frequencies, as shown in Fig. 3(c).

At Ω=459~519Hz, the vibration response manifests simple harmonic motion with the same frequency as excitation, namely a periodic motion. The waveform is similar to sine curve, and the excitation frequency is main frequency of frequency spectrum as shown in Fig. 3(d).

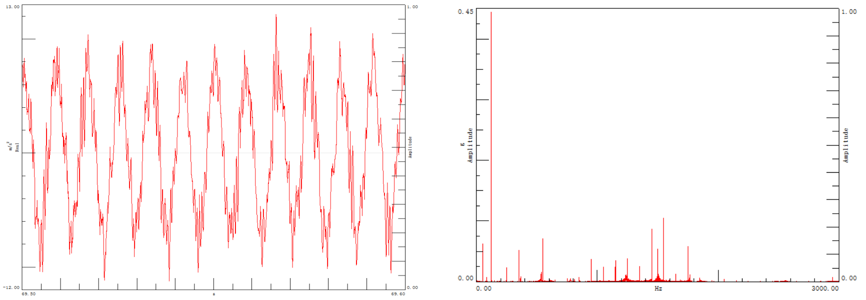
At Ω=620~760Hz, the vibration response manifests chaotic motion, as shown in Fig. 3(e) and 3(f).

At Ω=770~790Hz, the vibration response manifests double periodic motion, and the frequency spectrum includes excitation frequency and doubling excitation frequency, as shown in Fig. 3(g). The excitation frequency is considered as the cause of two-to-one internal resonance, because the excitation frequency $\Omega \approx 1/2 \times \omega 7$.

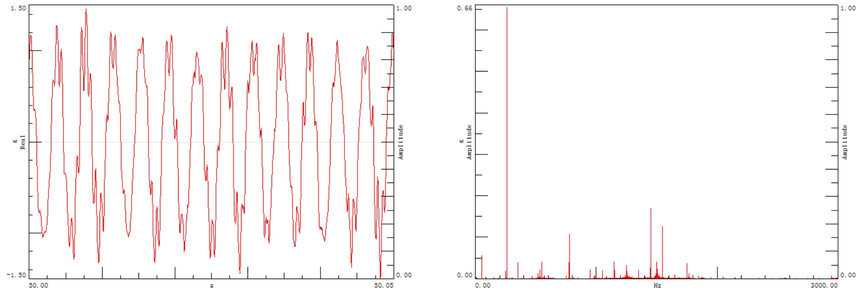
As excitation frequency increases, the vibration response transfers from chaotic motion (Ω=791~1059Hz, as Fig. 3(h)) to multi-periodic motion (Ω=1060~1318Hz, as Fig. 3(i)), to a periodic motion (Ω=1319~1760Hz, as Fig. 3(j)), to chaotic motion (Ω=1770~2200Hz, as Fig. 3(k) and 3(l)).



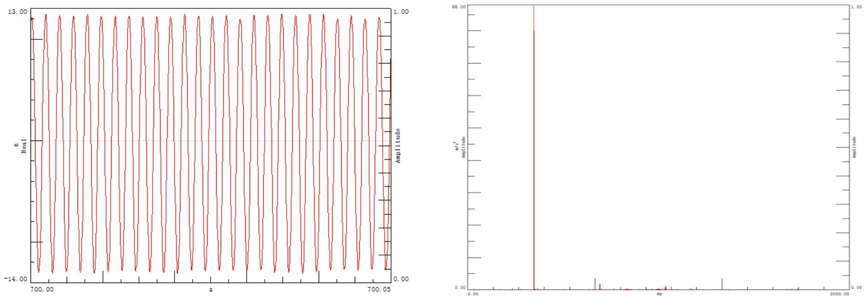
(a) Vibration response at $\Omega = 30$ Hz



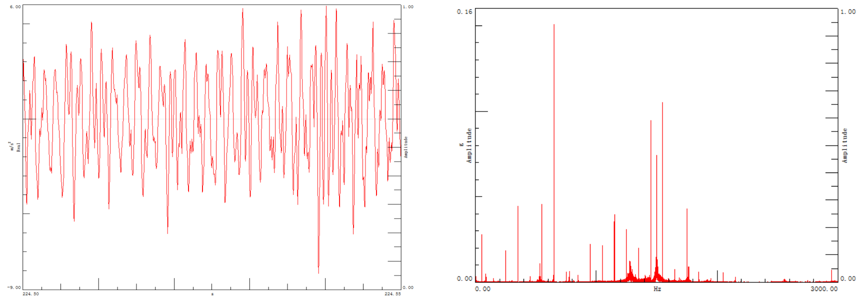
(b) Vibration response at $\Omega = 121.8$ Hz



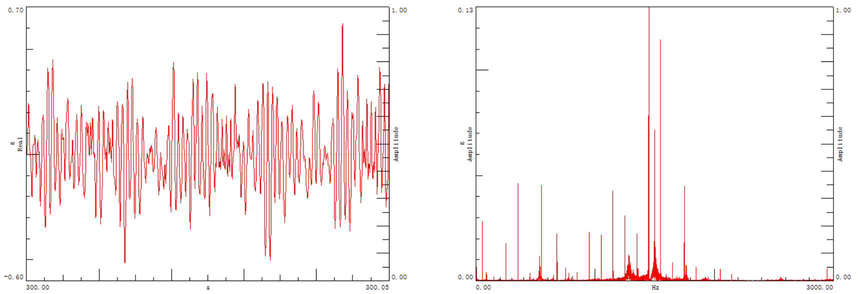
(c) Vibration response at $\Omega = 259$ Hz



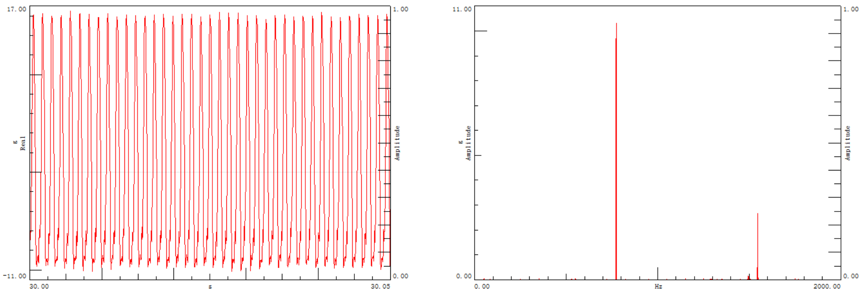
(d) Vibration response at $\Omega = 519$ Hz



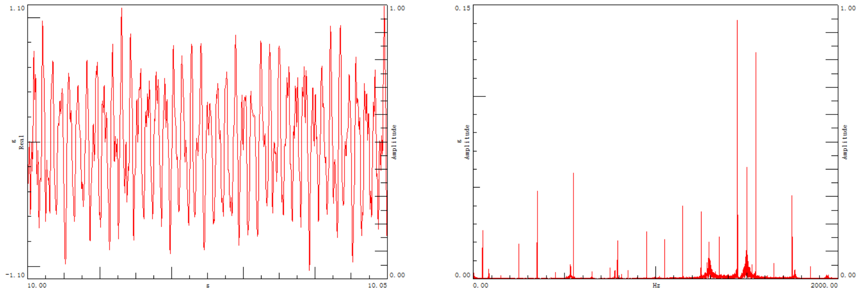
(e) Vibration response at $\Omega = 648.8$ Hz



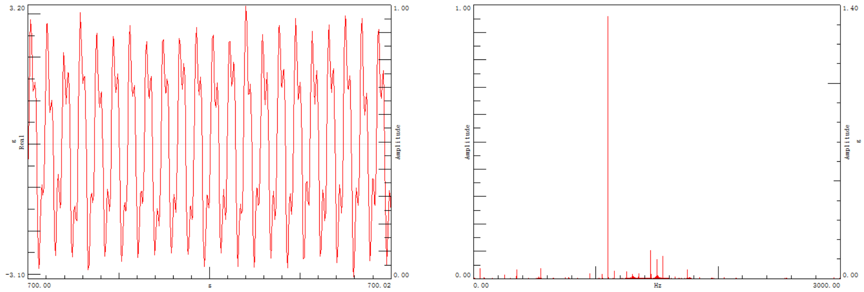
(f) Vibration response at $\Omega = 678.8$ Hz



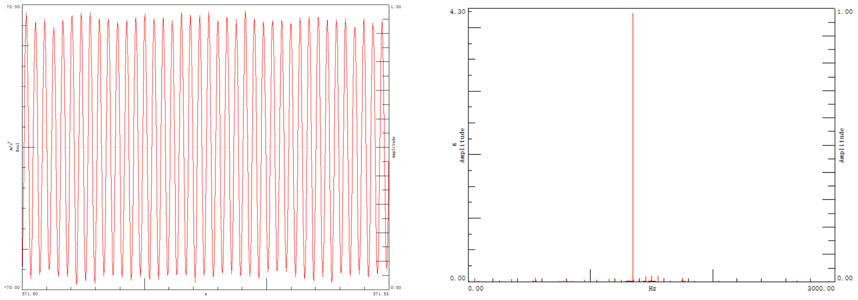
(g) Vibration response at $\Omega = 772.8$ Hz



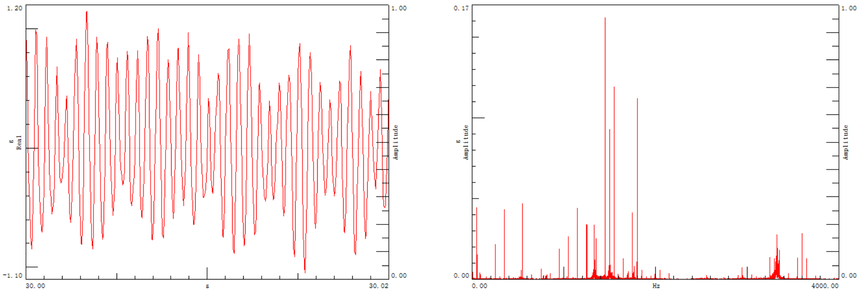
(h) Vibration response at $\Omega = 823$Hz



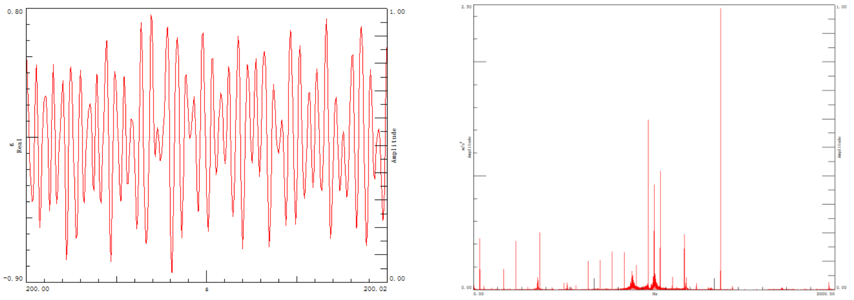
(i) Vibration response at $\Omega = 1099$ Hz



(j) Vibration response at $\Omega = 1346.6$ Hz



(k) Vibration response at $\Omega = 1800.4$ Hz



(l) Vibration response at $\Omega = 2054$ Hz

Fig. 3 Vibration responses of titanium alloy plate

3.2 Vibration response characteristics of hard-coating plate

According to the real-time measured response of hard-coating plate, excitation frequency can be divided into several frequency spectrums as shown in Fig. 4.

Under low frequency, namely Ω=30~140Hz, the vibration response of hard-coating plate manifests multi-periodic motion, and the frequency spectrum includes excitation frequency, the 3rd, the 6th and the 7th order natural frequency, as

Fig. 4(a) and 4(b).

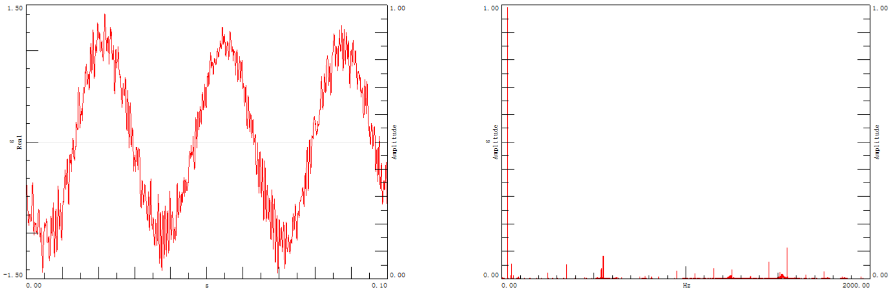
At Ω=140~440Hz, the vibration response manifests triple and quadruple periodic motion alternately, as Fig. 4(c) and 4(d).

At Ω=450~600Hz, the vibration response manifests simple harmonic motion with the same frequency as excitation, namely a periodic motion, as shown in Fig. 4(e). The waveform is similar to sine curve, and the excitation frequency is main frequency of frequency spectrum.

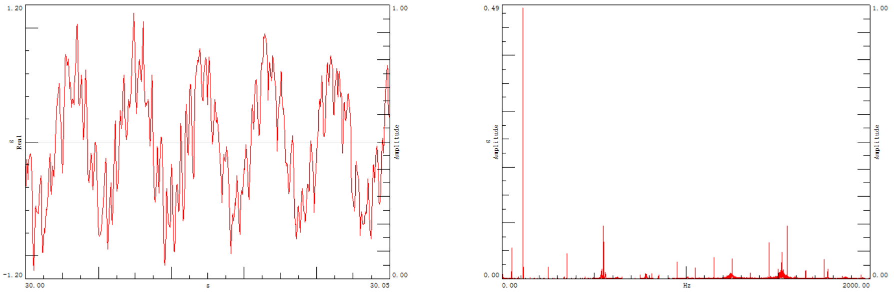
At Ω=600~716Hz, the vibration response manifests chaotic motion, as shown in Fig. 4(f).

At Ω=720~1110Hz, the vibration response manifests multi-periodic motion, as Fig. 4(g) and 4(i). Interestingly just at Ω≈842Hz, the vibration response transfers from multi-periodic to chaotic motion as Fig. 4(h), then retransfers back quickly.

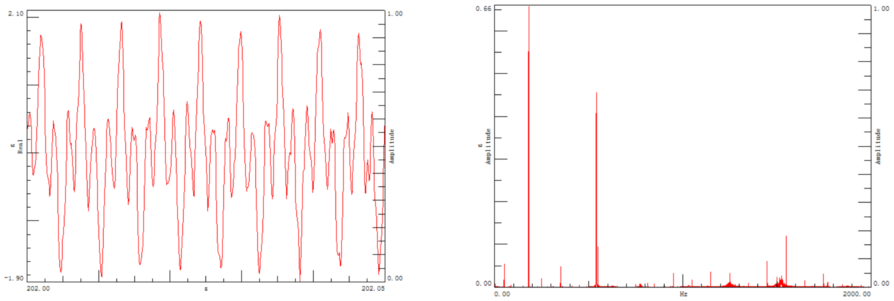
As excitation frequency increases, the vibration response transfers from a periodic motion (Ω=1110~1718Hz, as Fig. 4(j) and 4(k)) to quasi-periodic motion (Ω=1806~2200Hz, as Fig. 4(l) and 4(m)).



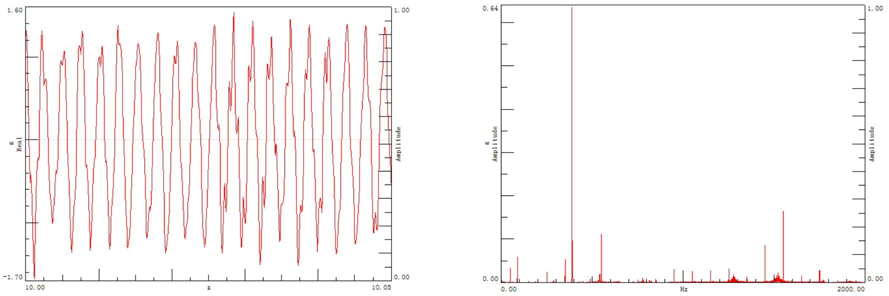
(a) Vibration response at $\Omega = 30$ Hz



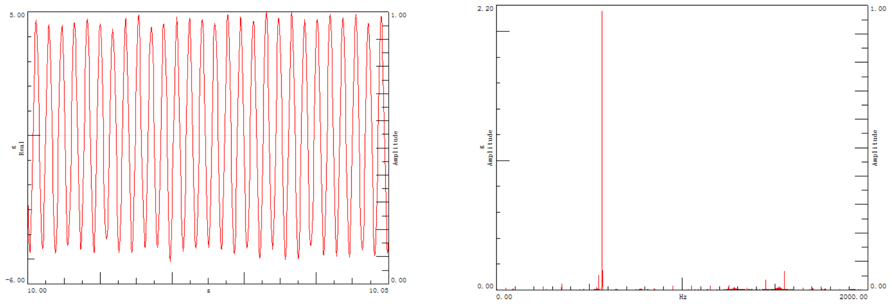
(b) Vibration response at $\Omega = 112$ Hz



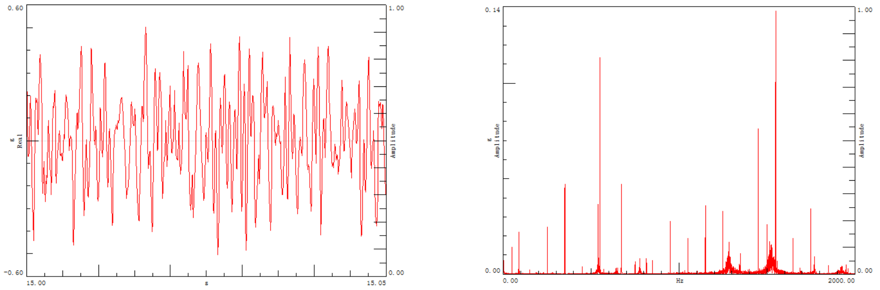
(c) Vibration response at $\Omega = 180.4$ Hz



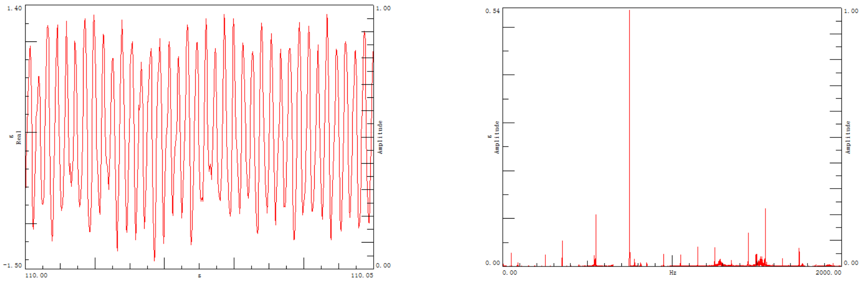
(d) Vibration response at $\Omega = 388$ Hz



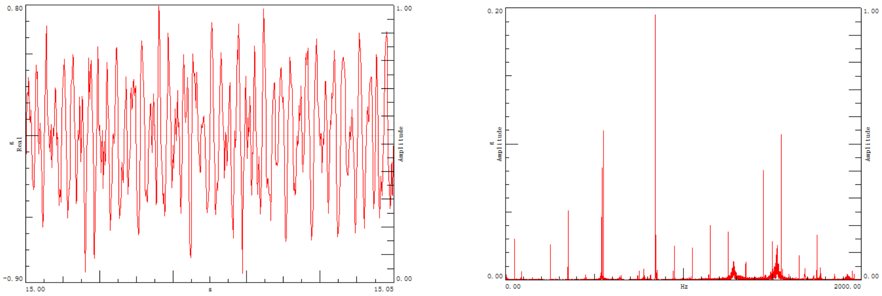
(e) Vibration response at $\Omega = 568$ Hz



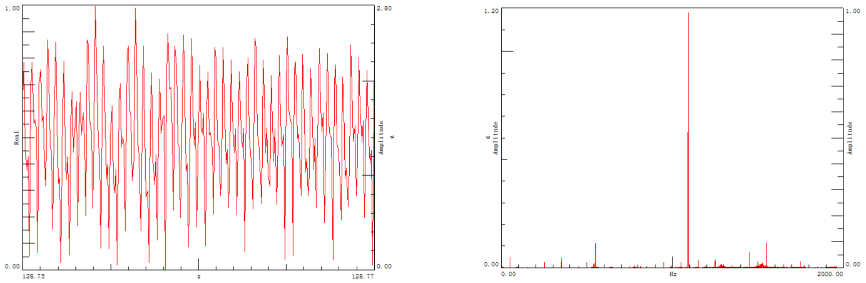
(f) Vibration response at $\Omega = 672$ Hz



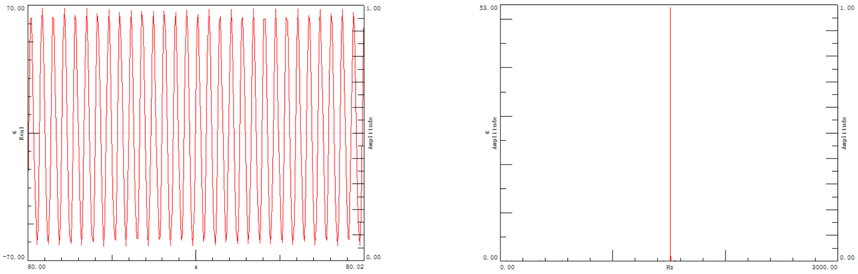
(g) Vibration response at $\Omega = 748$ Hz



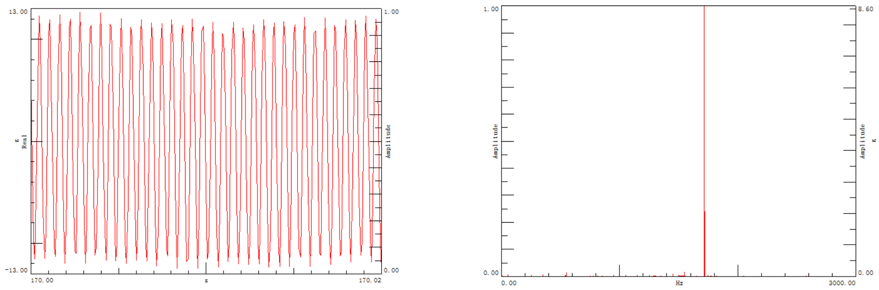
(h) Vibration response at $\Omega = 842$ Hz



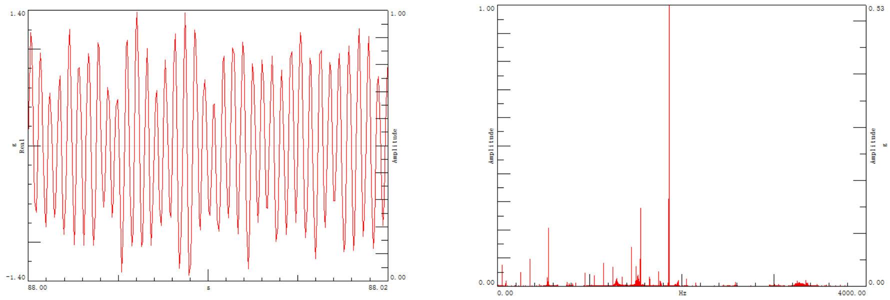
(i) Vibration response at $\Omega = 1092.8\,\mathrm{Hz}$



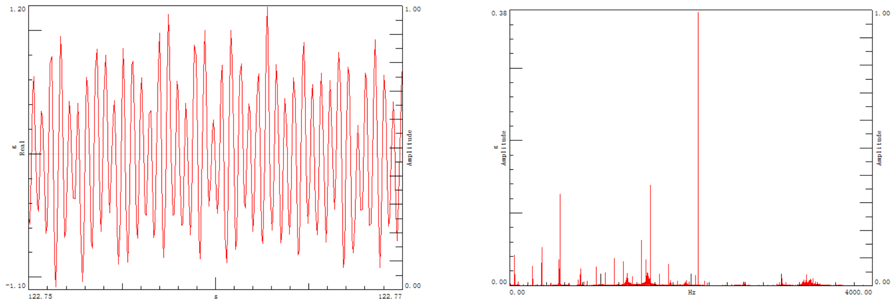
(j) Vibration response at $\Omega = 1512$ Hz



(k) Vibration response at $\Omega = 1718$ Hz



(l) Vibration response at $\Omega = 1860.4$ Hz



(m) Vibration response at $\Omega = 2078.2$ Hz

Fig. 4 Vibration responses of hard-coating plate

4 Discussion on the effect of hard coating on vibration behavior

To further compare the test results, the vibration response of titanium alloy plate and hard-coating plate are listed in the Table 2. The comparison shows that vibration characteristic of hard-coating plate is simpler, in the same excitation frequency spectrum. The vibration response of hard-coating plate mainly composites multi-periodic motion and simple harmonic motion.

Even more importantly, the results indicate that the damping performance of NiCrAlY coating is very remarkable, especially in high frequency spectrum. The hard-coating plate manifests chaotic motion in fewer spectrums (just at Ω=600~716Hz and Ω≈842Hz), compared with the three spectrums of titanium alloy plate (Ω=620~760Hz, Ω=791~1059Hz and Ω=1770~2200Hz). And in high frequency spectrum, the chaotic motion of titanium alloy plate is absolutely suppressed by NiCrAlY coating.

Tab. 2. vibration response of titanium alloy plate and hard-coating plate

titanium alloy plate		hard-coating plate	
Exciting frequency (Hz)	Response	Exciting frequency (Hz)	Response
30~190	multi-periodic motion	30~140	multi-periodic motion
210~439	quadruple periodic motion	140~440	triple and quadruple periodic motion
459~519	simple harmonic motion	450~600	simple harmonic motion
620~760	chaotic motion	600~716	chaotic motion
770~790	double periodic motion	720~1110	multi-periodic motion and chaotic motion
791~1059	chaotic motion	1110~1718	simple harmonic motion
1060~1318	multi-periodic motion	1806~2200	quasi-periodic motion
1319~1760	simple harmonic motion		
1770~2200	chaotic motion		

5 Conclusions

The nonlinear vibration behaviors of the cantilever hard-coating plate under transverse loading are experimentally investigated in this paper. In addition, the comparison test of vibration response is conducted between cantilever titanium alloy plate and cantilever hard-coating plate. Some useful conclusions are summarized as follows.

(1) Through the vibration response test, the nonlinear vibration behaviors of both titanium alloy plate and hard-coating plate are obtained under different excitation frequency.

(2) The comparison result indicates that the damping performance of NiCrAlY coating is very remarkable. The number of frequency spectra, in which the vibration response of hard-coating plate manifests chaotic motion, is much fewer than titanium alloy plate. Moreover, in high frequency spectrum, the chaotic motion is absolutely suppressed by NiCrAlY coating.

Acknowledgement

This work was financially supported by the National Natural Science Foundation of China (No.11472068), the General Scientific Research Program of Education department of Liaoning Province (L2015430) and the Doctor Starting Foundation of Liaoning Province (201601205).

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