Piezoelectric Vibration Control in Wind Tunnel Tests

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(Received 21 March 2021; revised 27 May 2021; accepted 31 May 2021)

Abstract: In wind tunnel tests, long cantilever stings are usually used to support aerodynamic models. However, this kind of sting support system is prone to vibration problems due to its low damping, which limits the test envelope and affects the data quality. It is shown in many studies that the sting vibration can be effectively reduced by using active sting dampers based on piezoelectric actuators. This paper attempts to review the research progress of piezoelectric vibration control in wind tunnel tests, covering the design of active sting dampers, control methods and wind tunnel applications. First of all, different design schemes of active sting dampers are briefly introduced, along with the vibration damping principle. Then, a comprehensive review of the control methods for active sting dampers is presented, ranging from classic control methods, like PID control algorithm, to various intelligent control methods. Furthermore, the applications of active sting dampers and controllers in different wind tunnels are summarized to evaluate their vibration damping effect. Finally, the remaining problems that need to be solved in the future development of piezoelectric vibration control in wind tunnel tests are discussed.

Key words: wind tunnel; sting vibration; active damper; piezoelectric actuator; active vibration control

CLC number: O34 **Document code:** A **Article ID:** 1005-1120(2021)03-0437-13

0 Introduction

It is well known that many mechanical structures, especially in the field of aerospace, are often subjected to vibrations introduced by operational or environmental effects, which are usually detrimental, resulting in structural fatigue and the decrease of safety[1-10]. Among various studies on the attenuation of vibration in aviation structures, this paper mainly discusses the recent research on vibration suppression of the cantilever sting support system used in wind tunnels.

Wind tunnel tests, which are usually operated to simulate flight environments and evaluate aerodynamic characteristics, are of vital importance in aircraft design process. To avoid support interference on test section flow, long cantilever stings are widely used in wind tunnels to mount test models. Generally, such cantilever sting support system consists of a test model, a wind tunnel balance and a tapered hollow sting connected to a rigid model attitude support system[11-13]. The length of the cantilever sting varies from three to five times the length of the model to avoid aerodynamic interference of the support system[14-15]. As the sting length increases, the damping and stiffness of the entire structure will be lower. As a consequence, undesirable large-amplitude and low-frequency vibrations occur easily on the sting support system when the test model sweeps to a large angle-of-attack or model flow separation appears, leading to test envelope limitation and data quality degradation. Moreover, this kind of harmful oscillations also result in wind tunnel balance overloads and threaten the safety of wind tunnel tests. In wind tunnel test history, many perfor-

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How to cite this article: SHEN Xing, HUANG Yun, ZHANG Lei, et al. Piezoelectric vibration control in wind tunnel tests [J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2021, 38(3): 437-449.

http://dx.doi.org/10.16356/j.1005-1120.2021.03.008

mance tests of wind tunnel models have been severely affected by the sting vibrations. Therefore, in order to ensure planed test envelope and obtain high-quality data, vibration suppression in wind tunnel tests has always been an active research topic.

Over the past decades, a variety of passive, active and hybrid control techniques to tackle structural vibration problems have been developed[16-22]. However, the current trend towards lightweight flexible structures leads to new challenges on vibration control technology. Conventional vibration damping materials and control methods are limited in a lot of applications involving flexible structures due to the inability of vibration control at low frequencies and the need for more space, energy and weight. The cantilever sting used in wind tunnel is one such flexible structure. The dynamic response of the sting support system exposed to wideband force excitation is dominated by low frequency modes. In addition, the test environments of wind tunnels also have strict restrictions, including space and flow field requirements. It is obvious that conventional control technology is not suitable for the vibration suppression in wind tunnels. In the early wind tunnel tests, passive control methods were mainly used to attenuate sting vibrations, such as using tuned mass dampers and viscoelastic materials[23-25]. The limitations of this method are that the low frequency vibration suppression effect is small, and each passive damper is only suitable for a specific test component, indicating that the passive damper may be less effective when the test component changes. As a result, considerable efforts to find new solutions for vibration control of the cantilever stings used in wind tunnels are constantly spared by many scholars and institutes.

In this context, the advent of smart materials has opened up new routes for vibration control of flexible structures. Among various smart materials, piezoelectric materials have emerged as the most widely used materials for vibration control, thanks to their excellent properties, such as lightweight, small volume, high electro-mechanical coupling coefficient, large frequency bandwidth of operation, and easy integration with flexible structures[26-30]. The principle of piezoelectricity can be divided into the direct piezoelectric effect and the converse piezoelectric effect. Piezoelectric materials will generate electric charges when subjected to mechanical loads (direct piezoelectric effect), and conversely, they will generate mechanical stress or strain when subjected to external electrical fields (converse piezoelectric effect). Based on converse piezoelectric effect, different types of piezoelectric actuators have been designed for active vibration control, which is the main application form of piezoelectric materials in wind tunnel tests[31-35].

The applications of piezoelectric materials in active vibration control provide wind tunnel researchers with a new idea for vibration damping. Up to now, many studies have been conducted on the use of piezo actuators to suppress sting vibrations. The Europe transonic wind-tunnel (ETW) first conducted the relevant research on active vibration control of cantilever stings using piezoelectric elements. A piezoelectric-based active damping device, called the anti-vibration-system (AVS) was developed to counteract vibrations in pitch plane of the sting support system[36-37]. Nevertheless, the vibration control effect of this system was not satisfactory for strong vibrations due to the drawbacks of structural design[38]. Based on the similar design philosophy, Balakrishna et al.[39-41] developed various active sting dampers using piezoelectric stack actuators according to different test models, and a series of evaluation tests were conducted in different wind tunnels, such as YiGYAN's low speed wind tunnel, NASA Langley Research Center National Transonic Facility (NTF) and Ames Research Center 11×11 Foot Transonic Wind Tunnel (11'TWT). Experimental results showed that the damping ratio of the support system and angle-of-attack testing range were greatly improved by using active piezoelectric sting dampers. However, most studies of ETW and NTF only focused on the design and validation tests of active sting dampers, and there were few studies on control algorithms. It is undoubtedly that control algorithms are vital to active vibration damping systems.

Recently, many scholars have also investigated the control algorithms for vibration suppression of the cantilever stings used in wind tunnels. The early research used the proportional integral derivative (PID) algorithm to control the piezoelectric actuators in active sting dampers[42]. Since it always takes a long time to obtain satisfying PID control parameters, novel intelligent control algorithms have aroused the interest of many researchers. Based on the PID algorithm, artificial neural network PID (NNPID) algorithm and linear quadratic regulator (LQR) optimal control algorithm, Shen et al.[43] developed three different controllers for active sting dampers, and the results indicated the superiority of intelligent control algorithms. Liu et al.[44] proposed a self-adaptive fuzzy PD control algorithm to control active sting dampers, which realized the self-tuning of PD control parameters.

A larger number of valuable results have been obtained in wind tunnel vibration control using piezoelectric actuators. However, exiguous review articles can be found in summarizing the relevant research results and the existing problems. In order to provide the necessary research background and the latest developments for the researchers interested in wind tunnel vibration control, this paper presents a review of piezoelectric vibration control in wind tunnel tests. Different design schemes of active sting dampers, as well as the vibration damping principle are reviewed according to the installing positions of piezo actuators. Various investigations on vibration control methods for active sting dampers are then discussed. Additionally, an assessment is made about the applications of active sting dampers and controllers in different wind tunnels. The final section discusses the shortcomings to be improved in the future developments.

1 Active Sting Dampers Using Piezoelectric Actuators

1.1 Structural design

As shown in Fig.1, the cantilever sting support system used in the wind tunnel can be regarded as a Bernoulli-Euler beam. The continuous sting system can be converted into a mass-stiffness-damping system with finite degrees of freedom by discretization, which can be represented by

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t)+\boldsymbol{C}\dot{\boldsymbol{x}}(t)+\boldsymbol{K}\boldsymbol{x}(t)=\boldsymbol{F}(t) \tag{1}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$, $\boldsymbol{K}$ are the mass, the damping and the stiffness matrixes; $\boldsymbol{F}(t)$ is the external force vector of the sting support system and $\boldsymbol{x}(t)$ the vibration displacement vector.

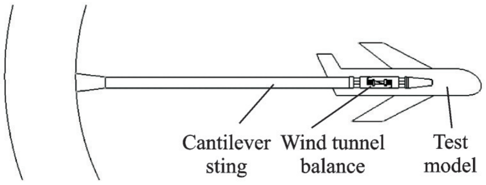
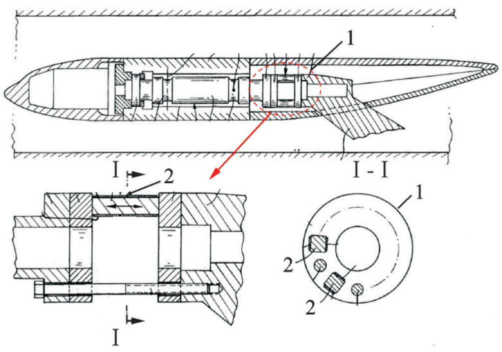


Fig.1 Schematic of a typical cantilever sting support system

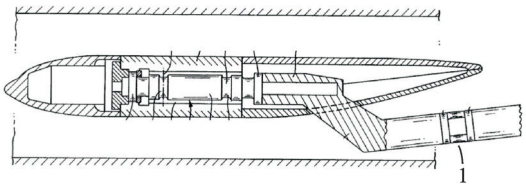
When no control force is acted on the sting support system, the external force vector can be expressed as $\boldsymbol{F}(t)=\boldsymbol{F}_{\text{aero}}(t)$, where $\boldsymbol{F}_{\text{aero}}(t)$ is the aerodynamic force vector. During wind tunnel tests, the aerodynamic force acting on the aircraft model can be divided into the static lift force, and the dynamic force excited by flow turbulence with multi-frequency components. The static force carries the aerodynamic information of the test model, while the dynamic force is the major cause of sting vibrations. Moreover, the sting support system tends to respond dynamically in eigen modes when exposed to aerodynamic forces. Generally, most wind tunnel sting support systems show six dominant eigen modes, including sting modes in pitch and yaw planes, coupled pitch-yaw sting modes manifesting as roll mode, modal-balance modes in pitch and yaw planes, and an axial translational modal-balance mode.

Since the slenderness of the cantilever sting is supposed to be as small as possible, the structural damping of the sting system is poor, resulting in large vibration amplitude and long oscillation duration. By appending extra damping to the sting, the vibration will be substantially reduced. Therefore, a lot of active sting dampers, which can improve the damping of the sting system, have been designed to suppress sting vibrations.

Hefer[36] from ETW proposed a piezoelectric-based active vibration damping device called the counter vibration generator in a patent for the sting support system used in wind tunnels. It is the first effective design scheme that applies piezoelectric elements to vibration control in wind tunnel tests. As shown in Fig.2(a), it was composed of six piezoelectric elements evenly distributed around the axis of the sting. The component 1 represents the counter vibration generator and the component 2 represents the piezoelectric element. Furthermore, it could be arranged not only between the sting and the wind tunnel balance, but also in the middle of the sting as shown in Fig.2(b).



(a) Components mounted between the sting and the wind tunnel balance



(b) Components mounted in the middle of the sting

Fig.2 Schematic of the counter vibration generator designed by Hefer[36]

According to Hefer's study, the design scheme was improved and an active AVS for full span model testing in the ETW was developed by Fehren et al[37]. As illustrated in Fig.3, the active damping structure which consisted of 14 piezoelectric actuators was installed between the 100 mm diameter flange of the six-component strain gauge balance and the sting. A carbon fiber sleeve was introduced to withstand the loads in terms of pressure, tension and shear, which enhanced the structural safety. Additionally, the vibrations in all degrees of freedom except the roll direction could be attenuated by using AVS.

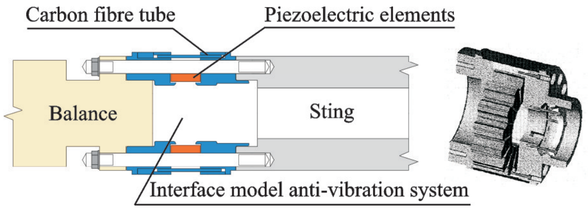


Fig.3 Schematic of ETW's AVS[37]

Similarly, the researchers from the NASA Langley Research Center NTF began to study vibration suppression of wind tunnel model support systems in the 1990s. Through the research on the dynamics of several standard models with violent vibration in wind tunnels, Young et al.[45] proposed the idea of applying smart materials to active vibration suppression. As a result, an active sting damper design concept[39] was presented in Balakrishna's study, which considered mounting a cluster of four piezoelectric devices in the sting, as shown in Fig.4. In this symmetric configuration, the piezo actuators were embedded with structural integrity in the sting in a cruciform pattern. Based on the balance signal feedback, the actuators could generate restoring moment in the pitch and yaw planes to counteract vibrations at the eigen frequencies of the sting system.

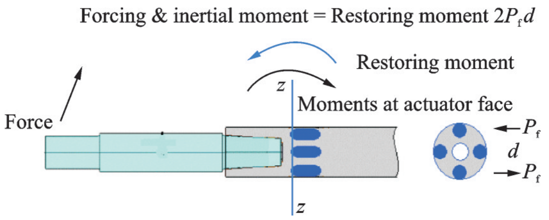


Fig.4 Design concept of an active sting damper using piezoelectric actuators[39]

The optimization of piezo-actuator cluster configuration was also investigated, as well as the mounting locations of the piezo-actuator cluster in the sting[40]. Two piezo cluster configurations and two types of active sting dampers were proposed as shown in Fig.5. The sting-tip damper was more suitable for high lift models, while the sting-root damper was more suitable for low lift models. Moreover, the piezo cluster configuration 1 could improve the structural rigidity of the sting system, compared with the second configuration. On this basis, three different types of active dampers were designed for the NTF Pathfinder-I check standard model, the crew launch vehicle (CLV) model and the NASA common research model (CRM), respectively[39-41,46-48].

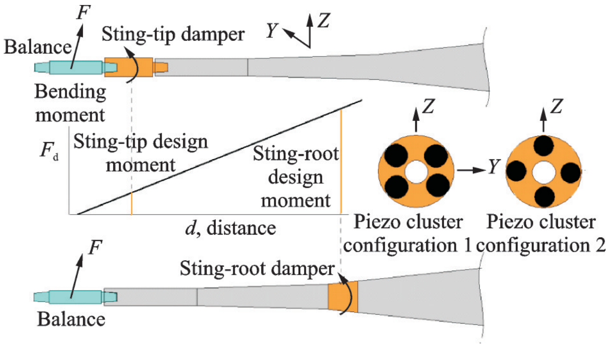


Fig.5 Configurations of the active sting damper[40]

In addition to the design of an active damper connected to the sting, the piezoelectric actuators can also be embedded in the sting directly. According to Liu's study, four piezoelectric stack actuators were embedded in the mounting grooves of the sting[44]. In order to ensure that the active damping device can output both pressure and tension, a pre-tightening mechanism was also designed in the mounting grooves. The schematic diagram of the active damping structure is shown in Fig.6.

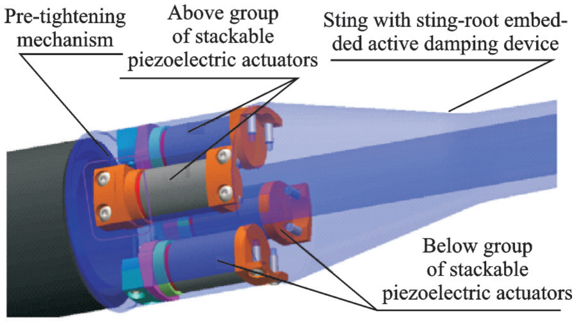


Fig.6 Schematic of the sting-root embedded active damping device[44]

It is well known that the output displacement of the piezoelectric stack actuator is in the micron order under electrode voltage, which limits the control performance of the active sting damper. Therefore, corresponding micro-displacement amplifiers have also been designed to improve the output performance of piezoelectric stack actuators. An active sting damper with a flexure hinge was proposed by Dai et al.[49] and four bolts were used to pre-tighten the piezoelectric actuators. Besides, only two high-voltage piezoelectric stack were used to generate the control force. Fig.7 shows the specific components of the active sting damper.

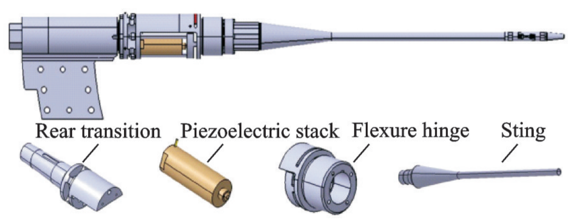


Fig.7 Components of the active sting damper with a flexure hinge[49]

1.2 Vibration damping principle

It can be concluded that all active sting dampers currently used in wind tunnel tests work according to the closed-loop feedback control theory. The principle of wind tunnel vibration reduction based on active sting dampers is illustrated in Fig.8. The aerodynamic load, composed of the static lift force and the wideband stochastic dynamic force, acts at the pressure center of the test model with zero moments, namely

$$F_{\mathrm{aero}}(t)=F_{\mathrm{s}}(t)+F_{\mathrm{d}}(t) \tag{2}$$

where $F_{\mathrm{s}}(t)$ and $F_{\mathrm{d}}(t)$ represent the static and dynamic forces, respectively.

Furthermore, the aerodynamic force will cause a bending moment that progressively increases along the axial direction of the cantilever sting. Then, the bending moment at the cross section of the active sting damper can be expressed as

$$M_{\mathrm{bending}}=F_{\mathrm{aero}}L \tag{3}$$

where L represents the distance between the section of the active sting damper to the center of pressure.

To counteract the bending moment that causes sting vibrations, the piezoelectric stack actuators are introduced in the active sting damper to generate an equal and opposite restoring moment, which can be expressed as

$$M_{\mathrm{restoring}}=nf_{\mathrm{pie}}d \tag{4}$$

where n represents the number of piezoelectric stack actuators, f_{pie} is the dynamic force generated by one piezoelectric stack, and d the distance from the equivalent action point of the piezoelectric stack to the neutral axis.

Hence, the net moment at the cross section of the active sting damper becomes zero, thereby suppressing the corresponding vibrations. However, it is noticeable that only the dynamic bending moment needs to be eliminated for vibration suppression. As a consequence, the time derivative of the bending moment is used as the feedback signal in the closed-loop control system. Such rate feedback enssures that the active sting damper will not work against the static moment generated in a wind tunnel test and only the dynamic moment is cancelled.

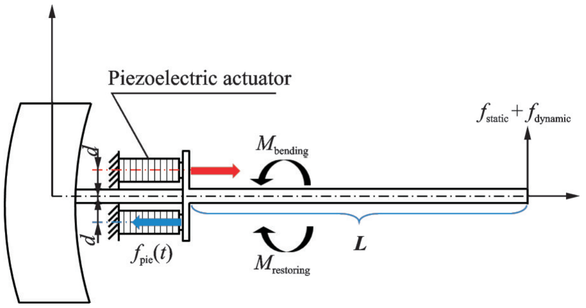


Fig.8 Principle of vibration suppression using the active sting damper

2 Control Methods for Wind Tunnel Vibration Suppression

The use of piezoelectric actuators for vibration suppression in wind tunnel tests has been proved to be effective. However, in addition to ensuring a good structural design of the active sting damper, it is also important to adopt appropriate control methods to improve the vibration damping performance. Based on the control algorithm, the research on various control methods used for wind tunnel vibration suppression can be divided into two categories: One covering the work in classic vibration control methods, and the other covering the studies with adaptive and intelligent methods.

2.1 Classic vibration control methods

2.1.1 PID controller

The first controller in question is the proportional, integral, and derivative (PID) controller. As the most widely used controller, the PID controller maintains a dominant position in engineering due to its robustness and universality. Similarly, it has been used by several researchers to suppress sting vibrations in wind tunnel tests[42,50]. A classical PID controller in a feedback loop is illustrated in Fig.9. The control output consists of PID components based on error signals. The mathematical expression in time domain is given as follows

$$u(t)=K_{\text{p}}e(t)+K_{\text{i}}\int_0^t e(\tau)\mathrm{d}\tau+K_{\text{d}}\frac{\mathrm{d}e(t)}{\mathrm{d}t} \tag{5}$$

where K_{p}, K_{i}, K_{d} are the proportional coefficient, the integral coefficient, and the derivative coefficient, respectively.

Considering that a digital implementation of a PID controller requires a discretization of the error signals, two discrete PID controllers are further developed by backward finite differences, namely the positional and incremental PID controllers.

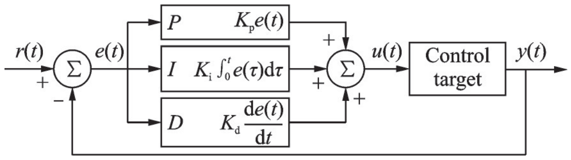


Fig.9 Diagram of a classical PID controller

Since the sting system will always turn back to the original equilibrium point after attenuation, there is no need to consider the steady-state error. As a result, the PID controller is mainly used in the actual damping applications. However, it is still a difficult problem for wind tunnel test engineers to adjust the control parameters to the optimal values of the desired control response, even though there are only three parameters to be determined. Besides, the values of control parameters usually need to be changed when the test model change for different wind tunnel tests, leading to great inconvenience for engineers.

2.1.2 LQR controller

Among the active vibration damping systems used in wind tunnels, the balance is located at the tip of the sting, while the piezoelectric stack actuators are arranged at the root of the sting, thereby forming a non-collocated configuration with the drawbacks of poor stability and robustness. Therefore, the LQR controller has been used to achieve the control of sting vibrations in wind tunnel tests[51]. In order to design the effective LQR controller, the state-space model of the sting system is essential and different system identification methods have been studied up to now, such as the observer/Kalman filter identification method and the state-space model identification method. In LQR design, the performance criteria for each mode of the sting system can be determined independently and the overall system cost can be calculated as the sum of all modal costs. The total quadratic performance index can be defined as

$$J_c = \sum_{i=1}^{n} J_i \tag{6}$$

where J_i is the performance cost of a single mode, and subscript i indicates the mode. n is the number of modes to be suppressed. The performance cost of a single mode can be assumed as

$$J_i = \int_0^t (\boldsymbol{x}_i^{\mathrm{T}} \boldsymbol{Q}_i \boldsymbol{x}_i + r_i u_i^2)\mathrm{d}t \tag{7}$$

where $\boldsymbol{Q}_i$ is the positive error weighted matrix and r_i a positive control weighted factor.

2.2 Adaptive and intelligent control methods

As mentioned above, most classical vibration control methods cannot adapt to the changes in controlled objects or environments, which limits the vibration damping performance. Especially for the PID controller, constant control parameters are not suitable for all tests models, and it usually takes a long time for wind tunnel test engineers to obtain the optimal values of control parameters again. With development of intelligent control theory, active vibration control of a variety of structures has been undertaken with many adaptive and intelligent controllers and the cantilever sting system used in wind tunnels is no exception.

2.2.1 Fuzzy PID controller

It is well known that the fundamental difficulty with the PID control is the tuning of control parameters. As a consequence, a self-adaptive fuzzy PID controller was proposed by Liu et al.[44] to realize control parameters adjustment automatically for various test conditions. According to the angle-of-attack, the airflow speed and the performance of the wind tunnel, the fuzzy rules were set based on the expert experience. As shown in Fig.10, the proportional and derivative parameters are adjusted according to the velocity error and the velocity error rate.

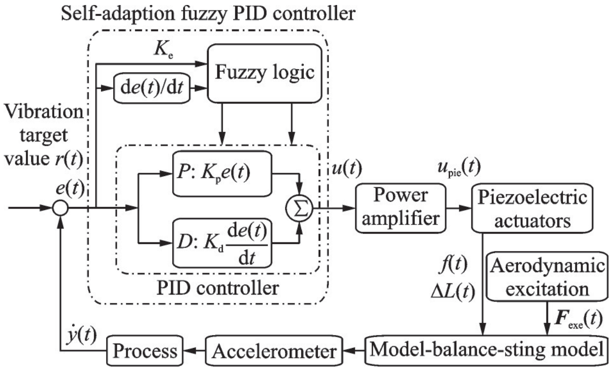


Fig.10 Schematic of self-adaptive fuzzy PID controller[44]

2.2.2 Neural network PID controller

In addition to the fuzzy-based intelligent controllers, neural networks are also widely used in the field of intelligent control due to their powerful self-learning capabilities. For the vibration control in wind tunnel tests, the research on neural networks mainly focuses on the design of neural network PID controllers, such as developing a self-learning PID controller based on a back propagation neural network (BPNN) with three layers[49-50]. Fig.11 shows a BPNN-PID controller in a feedback loop. The input layer has two neurons, which take the expected value and the actual value of vibration as inputs, while the hidden layer consists of three neurons functioning as the PID control parameters. The output layer obtains the control output by calculating the sum of the control parameters in the hidden layer.

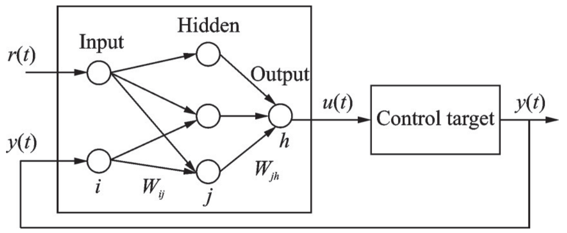


Fig.11 Schematic of a BPNN-PID controller with three layers[50]

Furthermore, the most extensive gradient descent (delta learning) rule is adopted to update the weight vectors. The formula for a BPNN-PID controller is

$$u(k)=K_{\mathrm{p}}(k)e_{\mathrm{p}}(k)+K_{\mathrm{i}}e_{\mathrm{i}}(k)+K_{\mathrm{d}}e_{\mathrm{d}}(k) \tag{8}$$

where

$$\begin{cases} e_{\mathrm{p}}(k)=r(k)-y(k)=-y(k) \\ e_{\mathrm{i}}(k)=\sum_{j=1}^{k}e_{\mathrm{p}}(j)=\sum_{j=1}^{k}[-y(j)] \\ e_{\mathrm{d}}(k)=e_{\mathrm{p}}(k)-e_{\mathrm{p}}(k-1)=-[y(k)-y(k-1)] \end{cases} \tag{9}$$

where $e_{\mathrm{p}}(k)$, $e_{\mathrm{i}}(k)$, $e_{\mathrm{d}}(k)$ are the errors of the proportional coefficient, the integral coefficient, and the derivative coefficient, respectively.

To save the resource of the self-tuning process, the learning rate β is usually set the same value for three control parameters. Then according to the delta learning rule, the chain rule, and the equivalent conversion, the final self-learning formula of the BPNN-PID can be described as

$$\begin{cases} K_{\mathrm{p}}(k+1)=K_{\mathrm{p}}(k)-\beta\,\mathrm{sgn}\left[\dfrac{y(k+1)-y(k)}{u(k)-u(k-1)}\right] \\ K_{\mathrm{i}}(k+1)=K_{\mathrm{i}}(k)-\beta\,\mathrm{sgn}\left[\dfrac{y(k+1)-y(k)}{u(k)-u(k-1)}\right] \\ K_{\mathrm{d}}(k+1)=K_{\mathrm{d}}(k)-\beta\,\mathrm{sgn}\left[\dfrac{y(k+1)-y(k)}{u(k)-u(k-1)}\right] \end{cases} \tag{10}$$

3 Wind Tunnel Applications

The large-amplitude and low-frequency vibrations of the cantilever sting used in wind tunnels have influenced the normal operation of many wind tunnel tests, which also restricts the development of a new generation of aircraft to a certain extent. To suppress such sting vibrations, different piezoelectric-based active damping devices and control methods have been developed and applied to the various wind tunnels. Here, we list the applications of these active sting dampers in wind tunnels, as well as their control methods.

Several typical wind tunnel applications of the active sting dampers are shown in Fig.12. It can be concluded that most of the active sting dampers are used in low-speed or transonic wind tunnels around the world, while there are few attempts in supersonic wind tunnels. Additionally, there are mainly two design schemes of the active sting damper, namely, the sting-tip damper and the sting-root damper. The sting-tip damper is designed to be mounted between the balance and the sting, which has poor structural rigidity. The sting-root damper is considered as an alternative to improve the structural rigidity. However, it also has higher requirement for the performance of piezoelectric actuators. Moreover, the long distance between actuators and sensors might

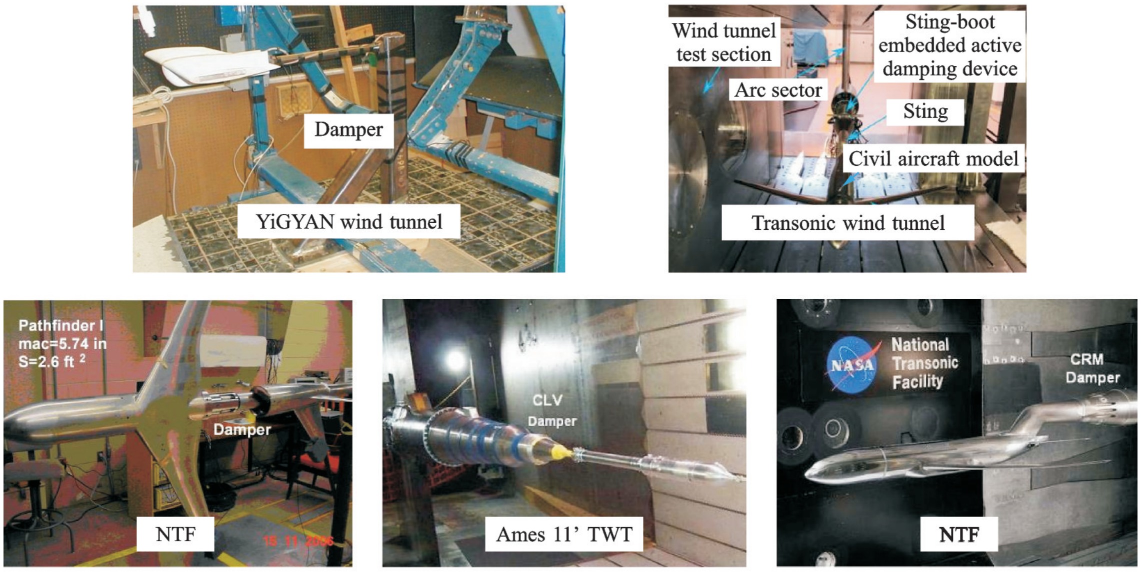
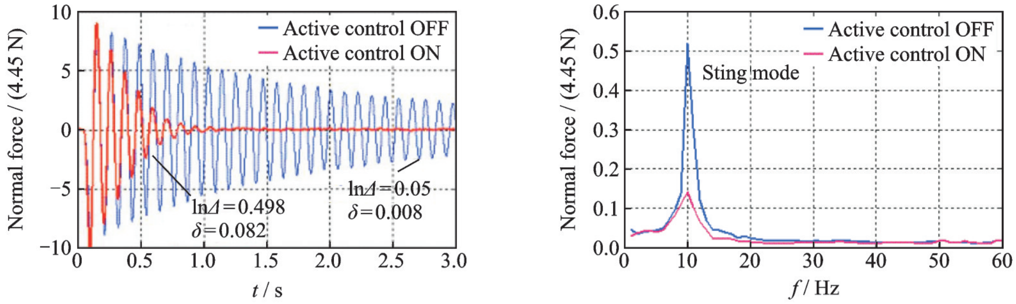
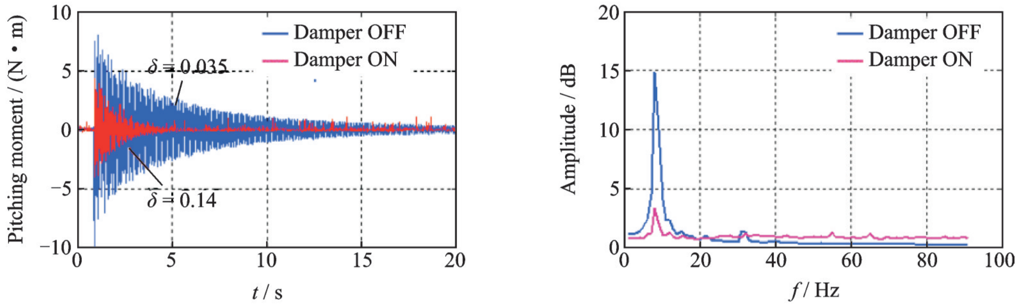


Fig.12 Photograph of active sting dampers in different wind tunnels[46-48]

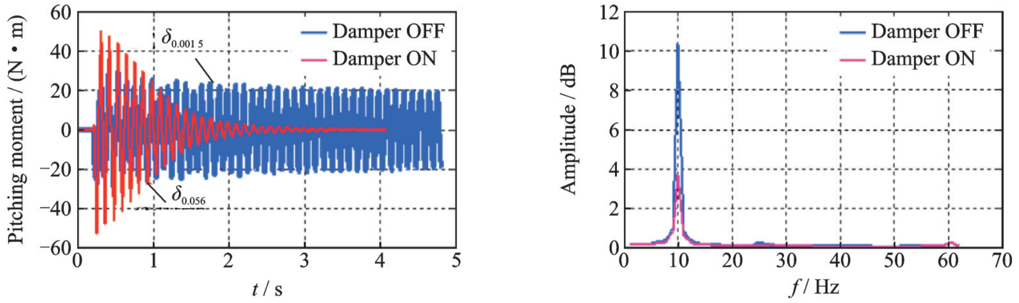
create spatial and temporal wave propagation issues, which needs to be considered in vibration control. In addition to active sting dampers, it is essential to use an effective control method for vibration suppression. However, most relevant foreign literatures did not present their control methods in detail. By contrast, the domestic scholars have conducted many research on wind tunnel vibration control methods. The control effects of the active damper with their control methods are shown in Fig.13. Since different models need to be evaluated in wind tunnel tests, most classic control methods will be less effective when the test model changes. As a result, increasingly more novel intelligent and adaptive control methods are investigated to suppress sting vibrations in wind tunnel tests. Various wind tunnel applications of the active sting dampers are concluded in Table 1.



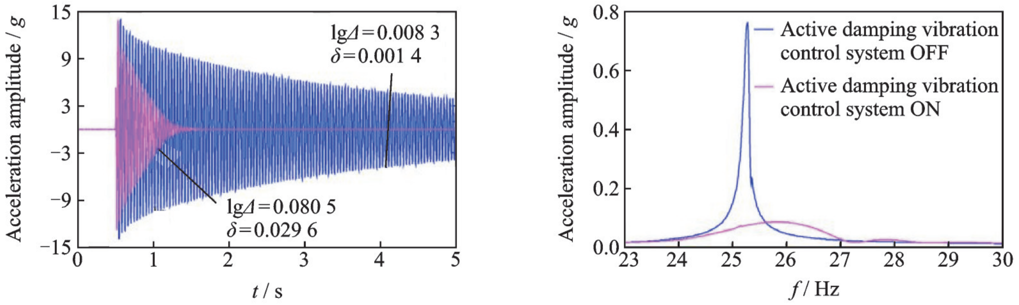
(a) Sting-tip dampers in YiGYAN wind tunnel[39]



(b) Sting-tip dampers in NTF[40]



(c) Sting-root dampers in Ames 11' TWT[40]



(d) Sting-root dampers in transonic wind tunnel[44]

Fig.13 Control effects of different active sting dampers with their control methods

Table 1 Wind tunnel applications of piezoelectric-based active sting dampers

Source	Wind tunnel	Active damping device	Control method	Vibration attenuation
Fehren et al.[37]	ETW	Sting-tip damper with 14 piezo actuators	Robust feedback controller	No detailed
Balakrishna et al.[39]	YiGYAN wind tunnel	Sting-tip damper with 4 piezo actuators	No detailed	15 dB attenuation
Balakrishna et al.[40]	NTF	Sting-tip damper with 4 piezo actuators	No detailed	80% attenuation
Balakrishna et al.[40]	Ames 11' TWT	Sting-root damper with 4 piezo actuators	No detailed	60% attenuation
Balakrishna et al.[41]	NTF	Sting-root damper with 12 piezo actuators	No detailed	No detailed
Liu et al.[44]	Transonic wind tunnel	Sting-root damper with 4 piezo actuators	Fuzzy PD controller	25 dB attenuation
Dai et al.[49]	Transonic wind tunnel	Sting-root damper with 2 piezo actuators	M-NNPID	26 dB attenuation

4 Conclusions

Over the past three decades, piezoelectric actuators have been widely used in active vibration control of various structures. Particularly in wind tunnel tests, extensive studies on the design of piezoelectric-based active sting dampers and control methods have been conducted to suppress the vibrations of the cantilever sting support system. This paper provides an overview of the recent developments of piezoelectric vibration control for wind tunnel tests. Two different types of active sting dampers are highlighted, according to the mounting locations of piezoelectric actuators. Both classic control methods and novel adaptive and intelligent control methods have been developed to improve the vibration damping effect. Furthermore, the extensive and impressive wind tunnel applications were investigated to prove the feasibility of using piezoelectric actuators for active vibration control of the cantilever stings.

Despite the significant progress, several issues that remains in the field of wind tunnel vibration control are worth probing, as detailed in the following.

(1) By means of piezoelectric stacks as damping devices, the sting vibrations in low-speed and transonic wind tunnels can be attenuated, which has been experimentally proved. However, the existing active sting dampers have not been widely applied to supersonic wind tunnels and there are few performance evaluation studies in supersonic wind tunnels. Future research should focus on the impact of different test conditions on the damp performance of active sting dampers and extend the application to supersonic wind tunnels.

(2) To increase the Reynolds number of wind tunnel tests, low-temperature wind tunnel has received more and more attention recently. Nevertheless, the driving performance of piezoelectric actuators will drop significantly at low temperatures. Although the wind tunnel researchers have noticed this problem, there is few relevant research on improving the control performance of active sting dampers at low temperature. Development of a heat preservation device with flexible temperature control ability is essential to solve this problem.

(3) Currently, the control target of most studies only focuses on the first pitch mode of sting vibrations while the higher order modes are not considered. In addition, when the test model is a bilateral symmetrical structure like a rocket or missile, it is necessary to suppress the vibration both in the pitch and yaw directions at the same time. For future developments of piezoelectric vibration control in wind tunnel tests, novel adaptive and intelligent control methods for multi-modal and multi-dimensional vibration should be designed to improve the effect of vibration reduction.

References

[1] GRIPP J A B, RADE D A. Vibration and noise control using shunted piezoelectric transducers: A review[J]. Mechanical Systems and Signal Processing, 2018, 112: 359-383.

[2] ZHANG Y, GUAN X. Active damping control of flexible appendages for spacecraft[J]. Aerospace Science and Technology, 2018, 75: 237-244.

[3] GAO Z, ZHU X, FANG Y, et al. Active monitoring and vibration control of smart structure aircraft based on FBG sensors and PZT actuators[J]. Aerospace Science and Technology, 2017, 63: 101-109.

[4] PRAKASH S, KUMAR T R, RAJA S, et al. Active vibration control of a full scale aircraft wing using a reconfigurable controller[J]. Journal of Sound and Vibration, 2016, 361: 32-49.

[5] XU R, LI D, JIANG J. An online learning-based fuzzy control method for vibration control of smart solar panel[J]. Journal of Intelligent Material Systems and Structures, 2015, 26(18): 2547-2555.

[6] YUAN Q, LIU Y, QI N. Active vibration suppression for maneuvering spacecraft with high flexible appendages[J]. Acta Astronautica, 2017, 139: 512-520.

[7] LUO Y, ZHANG X, ZHANG Y, et al. Active vibration control of a hoop truss structure with piezoelectric bending actuators based on a fuzzy logic algorithm[J]. Smart Materials and Structures, 2018, 27(8): 1-13.

[8] PU Y, ZHOU H, MENG Z. Multi-channel adaptive active vibration control of piezoelectric smart plate with online secondary path modelling using PZT patches[J]. Mechanical Systems and Signal Processing, 2019, 120: 166-179.

[9] OMIDI E, MAHMOODI S N, SHEPARD W S. Vibration reduction in aerospace structures via an optimized modified positive velocity feedback control[J]. Aerospace Science and Technology, 2015, 45: 408-415.

[10] FERRARI G, AMABILI M. Active vibration control of a sandwich plate by non-collocated positive position feedback[J]. Journal of Sound and Vibration, 2015, 342: 44-56.

[11] YOUNG C P, POPERNACK T G, GLOSS B B. National transonic facility model and model support vibration problems[C]//Proceedings of the 16th AIAA Aerodynamic Ground Testing Conference. [S. l.] : AIAA, 1990.

[12] SCHIMANSKI D, HEFER G. Recent aspects of high Reynolds number data quality and capabilities at the European transonic wind tunnel[C]//Proceedings of the 38th AIAA Aerospace Sciences Meeting and Exhibit Aerospace. [S.l.]: AIAA, 2000.

[13] SCHIMANSKI D, QUEST J. Tools and techniques for high Reynolds number testing status and recent improvements at ETW[C]//Proceedings of the 41st AIAA Aerospace Sciences Meeting and Exhibit. [S. l.]: AIAA, 2003.

[14] OCOKOLJIĆ G, RAŠUO B, KOZIĆ M. Supporting system interference on aerodynamic characteristics of an aircraft model in a low-speed wind tunnel[J]. Aerospace Science and Technology, 2017, 64: 133-146.

[15] RAŠUO B. Scaling between wind tunnels-results accuracy in two-dimensional testing[J]. Transactions of the Japan Society for Aeronautical & Spaceences, 2012, 55(2): 109-115.

[16] SAHU K C, TUHKURI J, REDDY J. Active piezoelectric-structure acoustic control of a soft-core sandwich panel using volume velocity and a weighted sum of spatial gradient control metric[J]. Journal of Vibration and Control, 2017, 23(15): 2391-2400.

[17] YUE H, LU Y, DENG Z, et al. Experiments on vibration control of a piezoelectric laminated paraboloidal shell[J]. Mechanical Systems and Signal Processing, 2017, 82: 279-295.

[18] LOGHMANI A, DANESH M, KWAK M K, et al. Vibration suppression of a piezo-equipped cylindrical shell in a broad-band frequency domain[J]. Journal of Sound and Vibration, 2017, 411: 260-277.

[19] MYSTKOWSKI A, KOSZEWNIK A P. Mu-synthesis robust control of 3D bar structure vibration using piezo-stack actuators[J]. Mechanical Systems and Signal Processing, 2016, 78: 18-27.

[20] WANG J. Active control for vibration distribution with performance specification and constraints[J]. Mechanical Systems and Signal Processing, 2019, 131: 112-125.

[21] LUO Y, ZHANG Y, XU M, et al. Improved vibration attenuation performance of large hoop truss structures via a hybrid control algorithm[J]. Smart Materials and Structures, 2019, 28(6): 1-16.

[22] SONG X, TAN S, WANG E, et al. Active shape control of an antenna reflector using piezoelectric actuators[J]. Journal of Intelligent Material Systems and Structures, 2019, 30(18/19): 2733-2747.

[23] CAPONE F J, IGOE W B. Reduction of wind-tunnel-model vibration by means of a tuned damped vibration absorber installed in the model: NASA TMX-1606 1968[R]. USA: NASA, 1968.

[24] FREYMANN R. Passive and active damping augmen-

tation systems in the fields of structural dynamics and acoustics[C]//Proceedings of the 30th Structures, Structural Dynamics and Materials Conference. [S. l.]: AIAA, 1989.

[25] GLAESE R, BALES G, HSU S, et al. Reduction of dynamic response of a wind tunnel sting mount using a hub damper unit[C]//Proceedings of AIAA Aerospace Sciences Meeting Including the New Horizons Forum & Aerospace Exposition. [S.l.]: AIAA, 2013.

[26] BENJEDDOU A. Shear-mode piezoceramic advanced materials and structures: A state of the art[J]. Mechanics of Advanced Materials and Structures, 2007, 14(4): 263-275.

[27] LANG S, MUENSIT S. Review of some lesser-known applications of piezoelectric and pyroelectric polymers[J]. Applied Physics A, 2006, 85(2): 125-134.

[28] SELIM B, ZHANG L, LIEW K. Active vibration control of CNT-reinforced composite plates with piezoelectric layers based on Reddy's higher-order shear deformation theory[J]. Composite Structures, 2017, 163: 350-364.

[29] SAVIZ M. An optimal approach to active damping of nonlinear vibrations in composite plates using piezoelectric patches[J]. Smart Materials and Structures, 2015, 24(11): 115024.

[30] KHAN A, LEE H S, KIM H S. Analysis of sensor-debonding failure in active vibration control of smart composite plate[J]. Journal of Intelligent Material Systems and Structures, 2017, 28(18): 2603-2616.

[31] PLATTENBURG J, DREYER J T, SINGH R. Vibration control of a cylindrical shell with concurrent active piezoelectric patches and passive cardboard liner[J]. Mechanical Systems and Signal Processing, 2017, 91: 422-437.

[32] STANTON S C, ERTURK A, MANN B P, et al. Nonlinear nonconservative behavior and modeling of piezoelectric energy harvesters including proof mass effects[J]. Journal of Intelligent Material Systems and Structures, 2012, 23(2): 183-199.

[33] PRESAS A, LUO Y, WANG Z, et al. A review of PZT patches applications in submerged systems[J]. Sensors, 2018, 18(7): 2251.

[34] KWAK M K, YANG D H. Active vibration control of a ring-stiffened cylindrical shell in contact with unbounded external fluid and subjected to harmonic disturbance by piezoelectric sensor and actuator[J]. Journal of Sound and Vibration, 2013, 332(20): 4775-4797.

[35] SONG G, SETHI V, LI H N. Vibration control of civil structures using piezoceramic smart materials: A review[J]. Engineering Structures, 2006, 28(11): 1513-1524.

[36] HEFER G. Wind tunnel model support with vibration detection balance and counter vibration means: US, US5644075 A[P]. 1997-07-01.

[37] FEHREN H, GNAUERT U, WIMMEL R, et al. Validation testing with the active damping system in the European transonic wind tunnel[C]//Proceedings of the 39th Aerospace Sciences Meeting and Exhibit. [S.l.]: AIAA, 2001.

[38] WIMMEL R. Active electronic equipment DOF suspension for high loads as vibration, shock and quasi static forces[C]//Proceedings of the European Conference on Spacecraft Structures, Materials and Mechanical Testing. [S.l.]: ESA, 2005.

[39] BALAKRISHNA S, HEATHER H, BUTLER D H, et al. Development of a wind tunnel active vibration reduction system[C]//Proceedings of the 45th AIAA Aerospace Sciences Meeting and Exhibit. [S. l.]: AIAA, 2007.

[40] BALAKRISHNA S, BUTLER D H, WHITE R, et al. Active damping of sting vibrations in transonic wind tunnel testing[C]//Proceedings of the 46th AIAA Aerospace Sciences Meeting and Exhibit. [S. l.]: AIAA, 2008.

[41] BALAKRISHNA S, BUTLER D, ACHESON M J, et al. Design and performance of an active sting damper for the NASA common research model[C]//Proceedings of the 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. [S.l.]: AIAA, 2011.

[42] CHEN J, SHEN X, TU F, et al. Experimental research on an active sting damper in a low speed acoustic wind tunnel[J]. Shock and Vibration, 2014, 2014(1): 164-178.

[43] SHEN X, DAI Y, CHEN M, et al. Active vibration control of the sting used in wind tunnel: Comparison of three control algorithms[J]. Shock and Vibration, 2018, 2018(9): 1-10.

[44] LIU W, ZHOU M, WEN Z, et al. An active damping vibration control system for wind tunnel models[J]. Chinese Journal of Aeronautics, 2019, 32(9): 2109-2120.

[45] YOUNG C P, HERGERT D W, BUTLER T W, et al. Buffet test in the national transonic facility[C]//Proceedings of the 17th Aerospace Ground Testing Conference. [S.l.]: AIAA, 1992.

[46] ACHESON M J, BALAKRISHNA S. Effects of active sting damping on common research model data quality[C]//Proceedings of the 49th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition. [S. l.]: AIAA, 2011.

[47] BALAKRISHNA S, ACHESON M. Analysis of NASA common research model dynamic data[C]// Proceedings of the 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. [S.l.]: AIAA, 2011.

[48] RIVERS M B, BALAKRISHNA S. NASA common research model test envelope extension with active sting damping at NTF[C]//Proceedings of the 32nd AIAA Applied Aerodynamics Conference. [S.l.]: AIAA, 2014.

[49] DAI Y, ZHANG L, ZHAO Z, et al. Wind-tunnel evaluation for an active sting damper using multimodal neural networks[J]. AIAA Journal, 2020, 58(4): 1-10.

[50] DAI Y, SHEN X, ZHANG L, et al. System identification and experiment evaluation of a piezoelectric-based sting damper in a transonic wind tunnel[J]. Review of scientific Instruments, 2019, 90(7): 075102.

[51] ZHANG L, DAI Y, SHEN X, et al. Research on an active pitching damper for transonic wind tunnel tests[J]. Aerospace Science and Technology, 2019, 94: 105364.

Acknowledgements This work was supported by the Foundation of National Key Laboratory on Ship Vibration and Noise (No. 614220400307), the National Natural Science Foundation of China (No.11872207), the Aeronautical Science Foundation of China (No. 20180952007), and the Foundation of State Key Laboratory of Mechanics and Control of Mechanical Structures (No. MCMS-I-0520G01).

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Competing interests All authors declare no competing interests.

(Production Editor: ZHANG Tong)

风洞试验中的压电振动控制

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摘要：风洞试验中常使用细长的悬臂支杆来支撑气动模型，但该支撑系统由于阻尼较低容易产生振动，从而限制了测试包线并影响数据质量。研究表明，通过使用基于压电作动器的主动式支杆阻尼器能有效抑制支杆振动。本文回顾了压电振动控制在风洞试验中的研究进展，包括主动阻尼器设计、控制方法设计和风洞应用3方面。首先分析主动阻尼器的不同设计方案及其减振原理；然后回顾用于主动阻尼器的控制方法，从经典控制方法（如PID控制）到各种智能控制方法；进一步总结主动阻尼器及其控制器在不同风洞中的实际应用，并评价其减振效果。最后，讨论风洞试验中的压电振动控制在未来发展中仍需要解决的问题。

关键词：风洞；支杆振动；主动阻尼器；压电作动器；振动主动控制