A VORTEX-INDUCED VIBRATION CONTROL METHOD FOR BRIDGE MAIN GIRDERS BASED ON PLASMA FLOW CONTROL

Field of the Invention

The present invention relates to the technical field of rapid prevention and control of wind-induced vibration risks for long-span bridges. More specifically, it relates to a vortex-induced vibration control method for bridge main girders based on plasma flow control.

Background to the Invention

Long-span bridges, due to their slender profiles and flexible characteristics, are wind-sensitive structures. In recent years, numerous incidents of severe vibrations in long-span bridges under wind action have occurred. On the afternoon of April 26, 2020, the Wuhan Yingwuzhou Yangtze River Bridge exhibited wave-like oscillations, causing dizziness and panic among drivers and passengers on the deck. On the afternoon of May 5, 2020, the Guangdong Humen Bridge experienced abnormal deck vibrations with a maximum vertical displacement reaching 44.61 cm, leading to a 10-day closure before reopening. On the evening of June 18, 2020, the Zhoushan Xihoumen Bridge vibrated continuously for approximately 70 minutes due to strong winds. Experts confirmed that these bridge girders underwent vortex-induced vibration (VIV) triggered by high winds. VIV is a vibration phenomenon caused by the periodic shedding of vortices. This demonstrates that VIV is a significant issue that cannot be overlooked during the service life of long-span bridges.

Vortex-induced vibration (VIV) is a type of wind-induced vibration in bridges. It has two primary characteristics: First, it can occur at relatively low wind speeds (e.g., Beaufort scale 3-5). Second, its amplitude is self-limiting. This implies a relatively high frequency of VIV occurrence. Although VIV does not cause catastrophic failure like galloping or flutter, frequent and sustained large-amplitude VIV can lead to member cracking, structural fatigue damage, pedestrian discomfort, compromised traffic safety and reduced bridge durability. Therefore, developing rapid VIV risk prevention and control technologies for long-span bridges is an urgent societal need.

Current flow control technologies commonly used for VIV suppression in long-span bridges fall into two categories: passive and active techniques. Passive flow control technologies frequently employed include aerodynamic appendages (e.g., spoilers, stabilizers), girder shape optimization (e.g., slotting the girder, adjusting the shape and position of railings and inspection track systems), and vortex generators. Chinese Patent No. CN106049248B discloses a VIV control method for long-span bridges using vertical-axis wind turbines. Vertical-axis wind turbines are installed beneath the main girder, utilizing the horizontal wake generated by their rotation under incoming flow to disrupt the regular vortex shedding from the girder cross-section. While this technique disrupts vortex shedding via rotating turbine wakes, its control effectiveness is not universally applicable to different bridge types. Real-world influencing factors are highly complex and constantly changing. When actual conditions deviate from the initial design scenario, control effectiveness often fails to reach optimum levels and may even adversely affect system performance.

Statement of Invention

The purpose of the present invention is to address the deficiencies in the prior art by providing a vortex-induced vibration control method for bridge main girders based on plasma flow control. Plasma actuators generate wall jets that suppress the formation and development of large-scale spanwise shedding vortices in the girder wake, effectively enhancing the VIV stability of long-span bridge girders.

The objective of the present invention is achieved through the following technical solution:

A vortex-induced vibration control method for bridge main girders based on plasma flow control, comprising the following steps:

S1. Plasma actuators are attached along the incoming flow direction to the upper surface and/or lower surface of the downstream fairing of the main girder;

S2. The plasma actuators are connected to a power supply, and subsequently, the power supply is connected to a control unit;

S3. The power supply is adjusted via the control unit. After being energized, the plasma actuators ionize the air near the surface to generate plasma. Under the action of an electric field, the plasma moves directionally to form a wall jet, thereby suppressing vortex-induced vibration.

Furthermore, in step S1, the plasma actuator comprises a dielectric insulator, an exposed electrode and an embedded electrode. The exposed and embedded electrodes are asymmetrically attached on either side of the dielectric insulator. Relative to the flow direction, the exposed electrode is located upstream of the embedded electrode.

Furthermore, in step S1, plasma actuators are arranged on the upper surface of the downstream fairing of the main girder. The adhesion of the actuators starts from the sharp corner where the fairing upper surface meets the girder top and continues along the upper surface at equal intervals.

Furthermore, in step S1, the plasma actuators are arranged on the lower surface of the downstream fairing of the main girder. The adhesion of the actuators starts from the sharp corner where the fairing lower surface meets the girder bottom and continues along the lower surface at equal intervals.

Furthermore, the number of plasma actuators is more than one, and the center distance between adjacent plasma actuators is 5-35 mm.

Furthermore, the plasma actuators are arranged at equal intervals.

Furthermore, exposed and embedded electrodes are made of copper foil, with a thickness of 0.01 mm to 0.1 mm and a width of 1 mm to 8 mm.

Furthermore, exposed and embedded electrodes are asymmetrically arranged on both sides of the dielectric material.

Furthermore, the shape of exposed and embedded electrodes is linear, serrated, wavy or rectangular.

Furthermore, the dielectric insulator is epoxy resin, organic glass, polyester film or polyimide film, with a thickness is 0.2-2 mm.

Compared with the existing technologies, the beneficial effects of the present invention are as follows:

(1) The present invention ionizes air passing over the plasma actuators to generate directional jets and create localized disturbances, eliminating the need for an additional air source. The invention can significantly reduce the structural weight and complexity of the control system. By altering parameters such as electrode shape, electrode geometry, dielectric thickness, and the number of plasma actuators, this invention achieves superior control effectiveness across various complex wind field environments, effectively suppressing vortex-induced vibrations.

(2) The invention enables electrified control of the device via the control unit. It allows powering on/off as needed and adjusting the ionization intensity of the actuators, achieving real-time active control.

Brief Description of the Drawings

Fig. 1 is a schematic structural diagram of a vortex-induced vibration control method for bridge main girders based on plasma flow control.

Fig. 2 is an enlarged cross-sectional view of the trailing-edge fairing of the main girder at A-A section in Fig. 1.

Fig. 3 is a schematic structural diagram of plasma actuators with different electrode shapes.

In the figures, 1 denotes an incoming flow direction, 2 denotes a main girder, 3 denotes a plasma actuator, 3a denotes an exposed electrode, 3b denotes an embedded electrode, 3c denotes an insulating insulator, 3d denotes a plasma, 3e denotes a wall jet, 4 denotes a power source, 5 denotes a control unit, 6 denotes a linear electrode, 7 denotes a serrated electrode, 8 denotes a wavy electrode, 9 denotes a rectangular electrode.

Detailed Description

The technical solutions of the present invention will be described clearly and comprehensively below, combining the drawings of specific embodiments. Clearly, the described embodiments are only part of the present invention embodiments, not all embodiments. Based on the embodiments of the present invention, all other embodiments obtained by those skilled in the art without making creative efforts are within the protection scope of the present invention.

Embodiment 1

This embodiment provides a vortex-induced vibration control method for bridge main girders based on plasma flow control, comprising the following steps:

S1. Plasma actuators 3 are attached along the incoming flow direction 1 to the upper or lower surfaces of the downstream fairing of the main girder 2. Each plasma actuator comprises a dielectric insulator 3c, with an exposed electrode 3a and an embedded electrode 3b asymmetrically attached on both sides of the dielectric insulator 3c. During the attachment, the exposed electrode 3a is positioned upstream of the embedded electrode 3b relative to the incoming flow direction 1.

S2. Plasma actuators 3 are connected to a power supply 4. The exposed electrode 3a and embedded electrode 3b are linked to the high-voltage output and low-voltage output of the power supply 4, respectively. Subsequently, the power supply 4 is connected to a control unit 5 and grounded.

S3. The power supply 4 is adjusted via the control unit 5. After being energized, the plasma actuators ionize air near the surface to generate plasma 3d. Under the action of an electric field, the plasma 3d moves directionally to form a wall jet 3e, thereby suppressing the vortex-induced vibration of the long-span bridge main girder 2.

Embodiment 2

As shown in Figs. 1-2, this embodiment provides an apparatus for implementing the plasma flow control-based vortex-induced vibration control method for bridge main girders described in Embodiment 1. The apparatus comprises a control unit 5, plasma actuators 3 attached to the upper surface of the downstream fairing of the main girder 2 along the incoming flow direction 1, and a power supply 4 connected to the plasma actuators. The plasma actuators 3 are mounted on the upper surface of the main girder's downstream fairing, starting from the sharp corner where the fairing meets the top of the main girder 2, with equidistant spacing along the surface.

Each plasma actuator 3 includes a dielectric insulator 3c, an exposed electrode 3a and an embedded electrode 3b asymmetrically attached on both sides of the dielectric insulator. Relative to the incoming flow direction 1, the exposed electrode 3a is positioned upstream of the embedded electrode 3b. The exposed electrode 3a and embedded electrode 3b are connected to the high-voltage and low-voltage outputs of the power supply 4, respectively. The power supply 4 is connected to the control unit 5 and grounded. The power supply 4 employs a low-temperature plasma source, and the control unit 5 functions as a voltage regulator for adjusting voltage magnitude. This enables electrical control to activate or deactivate the system on demand, modulate the ionization intensity of plasma actuators 3, and achieve real-time active control.

Multiple plasma actuators 3 are arranged equidistantly with a center-to-center spacing of 5-35 mm. Both electrodes 3a and 3b consist of copper foil with identical shapes, thicknesses of 0.01-0.1 mm, and widths of 1-8 mm. Electrode length is application-dependent and not further limited herein. The dielectric insulator 3c uses epoxy resin, organic glass, polyester film or polyimide film with a thickness of 0.2-2 mm.

After being energized, the plasma actuators 3 ionize near-surface air to generate plasma 3d. Under action of the electric field, the plasma 3d directionally moves to form a wall jet 3e that suppresses the formation and development of large-scale spanwise shedding vortices in the wake of main girder 2, thereby enhancing vortex-induced vibration stability for long-span bridge girders. Vibration suppression effectiveness significantly increases with greater dielectric thickness or higher plasma actuator's numbers.

Operational workflow: When the incoming wind speed reaches the vortex-resonance velocity of main girder 2, the control unit 5 delivers high-frequency high-voltage power to the actuators 3 via the low-temperature plasma power supply 4. The actuators 3 ionize near-surface air to generate plasma 3d. Under the action of the electric field, plasma 3d undergoes directional movement to form a wall jet 3e, thereby suppressing the formation and development of large-scale spanwise shedding vortices in the wake of main girder 2.

Embodiment 3

This embodiment provides an apparatus for implementing the plasma flow control-based vortex-induced vibration control method for bridge main girders described in Embodiment 1. The apparatus comprises a control unit 5, plasma actuators 3 attached to the downstream fairing of the main girder 2 along the incoming flow direction 1, and a power supply 4 connected to the plasma actuators. Distinct from Embodiment 1, the plasma actuators 3 are mounted on the lower surface of the downstream fairing, starting from the sharp corner where the fairing meets the bottom of main girder 2, with equidistant spacing along the surface.

Each plasma actuator 3 includes a dielectric insulator 3c, an exposed electrode 3a and an embedded electrode 3b asymmetrically attached on both sides of the dielectric insulator. Relative to the incoming flow direction 1, the exposed electrode 3a is positioned upstream of the embedded electrode 3b. The exposed electrode 3a and embedded electrode 3b are connected to the high-voltage and low-voltage outputs of the power supply 4, respectively. The control unit 5 functions as a voltage regulator for adjusting voltage magnitude. This enables electrical control to activate or deactivate the system on demand, modulate the ionization intensity of plasma actuators 3, and achieve real-time active control.

Multiple plasma actuators 3 are arranged equidistantly with a center-to-center spacing of 5-35 mm. Both electrodes 3a and 3b consist of copper foil with identical shapes, thicknesses of 0.01-0.1 mm, and widths of 1-8 mm. Electrode length is application-dependent and not further limited herein. The dielectric insulator 3c uses epoxy resin, organic glass, polyester film or polyimide film with a thickness of 0.2-2 mm.

After being energized, the plasma actuators 3 ionize near-surface air to generate plasma 3d. Under action of the electric field, the plasma 3d directionally moves to form a wall jet 3e that suppresses the formation and development of large-scale spanwise shedding vortices in the wake of main girder 2, thereby enhancing vortex-induced vibration stability for long-span bridge girders. Vibration suppression effectiveness significantly increases with greater dielectric thickness or higher plasma actuator’s numbers.

Operational workflow: When the incoming wind speed reaches the vortex-resonance velocity of main girder 2, the control unit 5 delivers high-frequency high-voltage power to the actuators 3 via the low-temperature plasma power supply 4. The actuators 3 ionize near-surface air to generate plasma 3d. Under the action of the electric field, plasma 3d undergoes directional movement to form a wall jet 3e, thereby suppressing the formation and development of large-scale spanwise shedding vortices in the wake of main girder 2.

Embodiment 4

As shown in Figs. 1-2, this embodiment provides an apparatus for implementing the plasma flow control-based vortex-induced vibration control method for bridge main girders described in Embodiment 1. The apparatus comprises a control unit 5, plasma actuators 3 attached to the upper and lower surfaces of the downstream fairing of the main girder 2 along the incoming flow direction 1, and a power supply 4 connected to the actuators. The plasma actuators 3 are mounted on both the upper surface (starting from the sharp corner at the top junction with main girder 2) and lower surface (starting from the sharp corner at the bottom junction with main girder 2), with equidistant spacing along both surfaces.

Each plasma actuator 3 includes a dielectric insulator 3c, an exposed electrode 3a and an embedded electrode 3b asymmetrically attached on both sides of the dielectric insulator. Relative to the incoming flow direction 1, the exposed electrode 3a is positioned upstream of the embedded electrode 3b. The exposed electrode 3a and embedded electrode 3b are connected to the high-voltage and low-voltage outputs of the power supply 4, respectively. The power supply 4 is connected to the control unit 5 and grounded. The control unit 5 enables electrical control to activate or deactivate the system on demand, modulate the ionization intensity of plasma actuators 3, and achieve real-time active control.

Multiple plasma actuators 3 are arranged equidistantly with a center-to-center spacing of 5-35 mm. Both electrodes 3a and 3b consist of copper foil with identical shapes, thicknesses of 0.01-0.1 mm, and widths of 1-8 mm. Electrode length is application-dependent and not further limited herein. The dielectric insulator 3c uses epoxy resin, organic glass, polyester film or polyimide film with a thickness of 0.2-2 mm.

After being energized, the plasma actuators 3 ionize near-surface air to generate plasma 3d. Under action of the electric field, the plasma 3d directionally moves to form a wall jet 3e that suppresses the formation and development of large-scale spanwise shedding vortices in the wake of main girder 2, thereby enhancing vortex-induced vibration stability for long-span bridge girders. Vibration suppression effectiveness significantly increases with greater dielectric thickness or higher plasma actuator’s numbers.

As shown in Fig. 3, this embodiment achieves enhanced control effectiveness in complex wind field environments by adjusting parameters including electrode shape, geometric dimensions, dielectric thickness, and the number of plasma actuators. Specifically, the exposed electrode 3a and embedded electrode 3b may adopt configurations such as the linear electrode 6, serrated electrode 7, wavy electrode 8 or rectangular electrode 9.

Operational workflow: When the incoming wind speed reaches the vortex-resonance velocity of main girder 2, the control unit 5 delivers high-frequency high-voltage power to the actuators 3 via the low-temperature plasma power supply 4. The actuators 3 ionize near-surface air to generate plasma 3d. Under the action of the electric field, plasma 3d undergoes directional movement to form a wall jet 3e, thereby suppressing the formation and development of large-scale spanwise shedding vortices in the wake of main girder 2.

It should be noted that the directional indications (such as up, down, left, right, front, rear, etc.) used in the present embodiment are only intended to explain the relative positional relationships and movements of the components in a specific orientation (as shown in the drawings). If the specific orientation changes, the directional indications change accordingly.