Trial of Large Gap Using Superconducting Magnetic Suspension System

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Abstract
Superconducting technique is applied to a suspension system. Persistent current in superconducting coil and control current in copper coil are used for suspending object and controlling object, respectively. The system is composed of a superconducting coil, a copper coil, a suspended object, a photo sensor, a PID controller, and power amplifiers. In this paper, basic study on superconducting coil and solenoid coil, and the dynamic characteristics of the suspended object are performed. As a result, it is found that the suspended object continues to levitate at a distance 43 mm for ≈15 s. This may be the first trial that superconducting coil is used for magnetic suspension.

Keywords : Magnetic bearing, Magnetic suspension, Superconducting suspension, Superconducting coil

1. Introduction

Magnetic suspension technique is a very promising technology because of the absence of mechanical contact (Joshi, et al., 1991), (Kawamura, et al., 2013). In general, magnetic suspension technique uses electromagnets (EMs) for controlling the positions of suspended objects. When EMs are applied to suspension systems, much electrical power is necessary for suspending them. On the other hand, wind tunnel test equipment with an airplane model needs a mechanical support to keep it in the center of the wind tunnel. However, the wind tunnel needs nothing around the model, because the mechanical support disturbs the environment around the airplane model (or other models). Then, in order not to disturb the environment, magnetic suspension technique is very promising for wind tunnel test equipments.

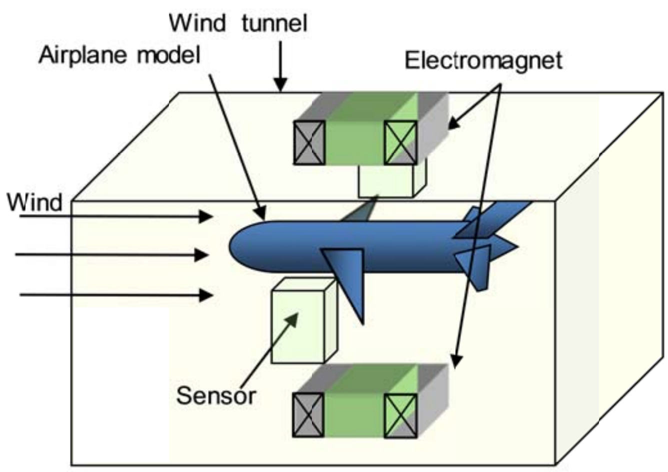


Fig.1 Wind tunnel test equipment with an airplane model supported by a magnetic suspension system. Wind tunnel test equipments are composed of an airplane model, some electromagnets for magnetic suspension, some displacement sensors for detecting the positions, etc.

Using magnetic suspension technology, a wind tunnel test equipment is proposed as shown in Fig. 1. The test equipment is composed of an airplane model, some EMs for suspension and some displacement sensors for detecting model position. In order to increase the distance between EMs and airplane model (suspended object), much larger electromagnetic forces for suspended object are needed. Then, much larger current and much larger electrical power are needed to suspend object and control it. However, in order to get larger current and electrical power, there is a technical limit to conventional EMs systems.

Then, in this paper superconducting technique is applied to a suspension system such as a wind tunnel test equipment (Hull, et al., 1995), (Komori, et al., 1998), (Nakaya, et al., 2013). Especially, applying superconducting coils are suitable for improving systems. Persistent current in superconducting coil and control current in copper coil are used for suspending object and controlling object, respectively. There is no electrical power loss in superconducting coil because there is no electric resistance of superconducting coil (Igarashi, et al., 2004). In this paper, trial of large gap using superconducting coil and solenoid coil are performed, and dynamic characteristics of suspended object are studied. This may be the first trial in which superconducting coils are used for magnetic suspension.

2. Superconducting Magnetic Suspension System

Fig. 2 shows a schematic illustration of a wind tunnel test equipment with a suspended object supported by a magnetic suspension system. This system is just a suspension system for studying a wind tunnel test equipment using superconducting technique. The system is composed of a superconducting coil, a copper coil, a suspended object, a photo sensor, a PID controller and a power amplifier. The copper coil (Φ 0.3 mm ×500 turns) measures 40 mm in outer diameter, 10 mm in inner diameter and 11 mm in thickness, which is set inside the superconducting coil to avoid the mutual influence between the copper coil and the superconducting coil. The superconducting coil and the copper coil are immersed in liquid nitrogen inside the container, and are used for suspending object and controlling object, respectively. In the experiment, persistent current is applied to the superconducting coil and control current is applied to the copper coil. The suspended object (Φ 28.0 ×100 mm, 68.0 g) has permanent magnets (PMs) at the both ends. The photo sensor is used for detecting the distance of suspended object. Fig. 3 shows the superconducting coil (BiSCCO) for studying persistent current. The superconducting coil measures 103.4 mm in outer diameter, 60 mm in inner

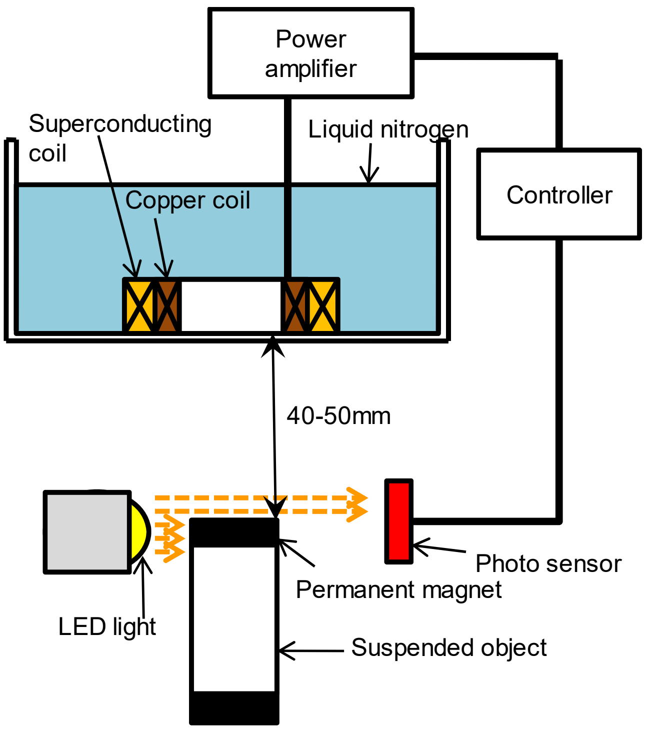


Fig.2 Superconducting magnetic suspension system for wind tunnel test equipments. The magnetic suspension system is composed of a superconducting coil (BSCOO), a copper coil (0.3 mm), a magnetically suspended object, a photo sensor, a PID controller and power amplifiers.

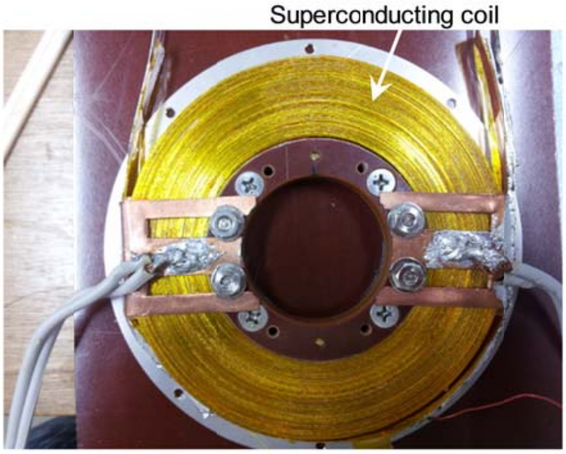


Fig.3 Superconducting coil for suspended object A copper coil is installed inside the superconducting coil. In the experiments the superconducting coil and the copper coil are in a liquid nitrogen container.

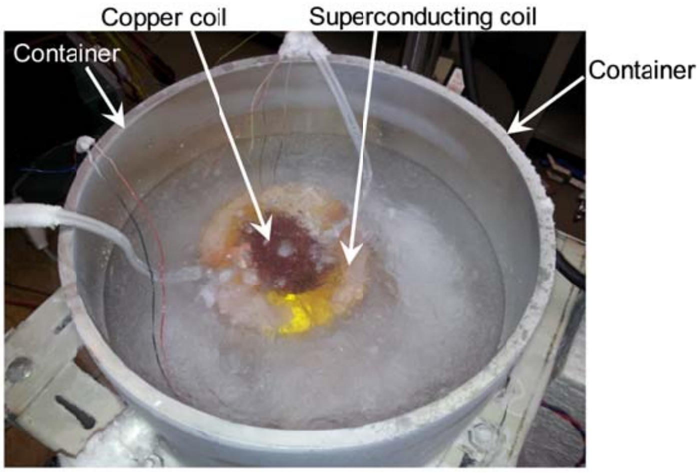


Fig.4 Superconducting coil and copper coil working in liquid nitrogen in a liquid nitrogen container. During some experiments, the superconducting coil is in the same condition as this photo.

diameter and 10 mm in thickness. The maximum permitted current of the superconducting coil is 160 A.

Fig. 4 shows that the superconducting coil and the copper coil are in liquid nitrogen and work in liquid nitrogen. The superconducting coil and the copper coil are set at the bottom of the container. During some experiments, the superconducting coil is in the same condition as shown in Fig. 4.

3. Attractive force characteristics

Attractive forces between the superconducting coil and the PM are measured. In the experiment, the current from 0 to 100 A is applied to the superconducting coil. Fig. 5 shows the relationship between attractive force and driving current for a distance 50.0 mm between the superconducting coil surface and the PM surface. The figure shows the linear relationship between force and current. The attractive force at a current of 90 A is corresponding to the weight (68.0 g) of the suspending object. Although the distance 50 mm is very large, the attractive force can be applied to the suspended object weight 68.0 g. The current 90 A is very large compared with several ampere for conventional suspension systems

Attractive forces between the superconducting coil and the PM are measured in the distance range from 35 mm to 45 mm. In the experiment, the distance is changed from 45 mm to 35 mm keeping the current of 70A. The initial distance is set at 43 mm. The experimental result is shown in Fig. 6. With increasing distance, the attractive force

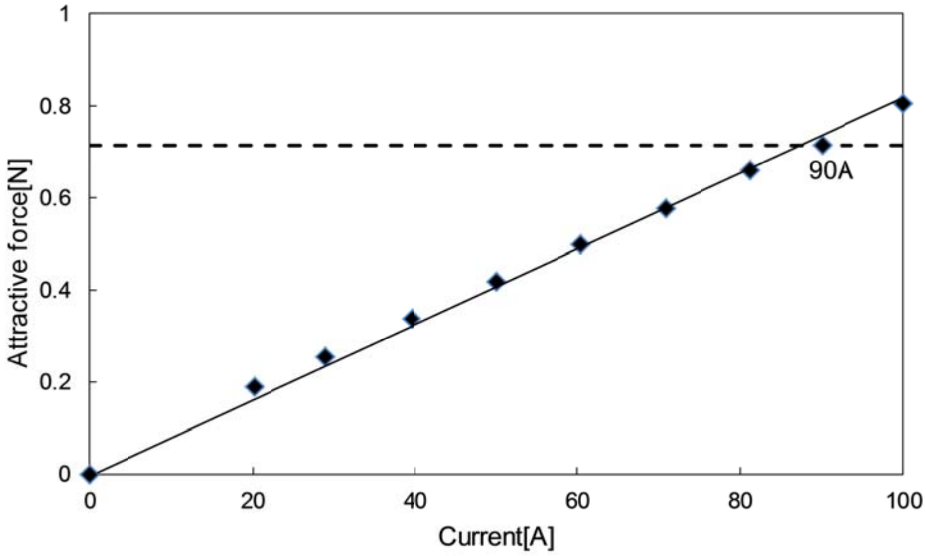


Fig.5 Relationship between attractive force and applied current to the superconducting coil. The relationship is almost linear over the wide current range. The attractive force 0.68 N corresponding to the suspended object weight is supported by an applied current 90 A.

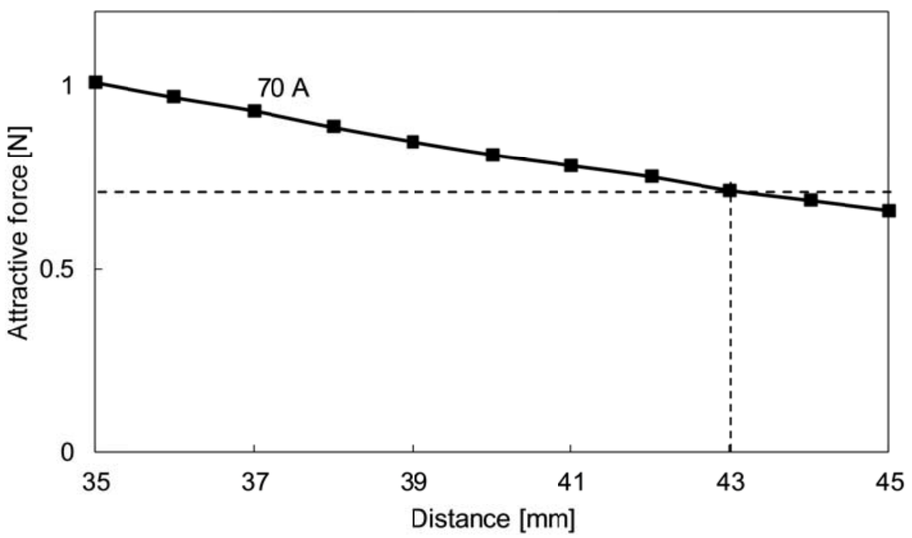


Fig.6 Relationship between attractive force and gap for a applied current 70 A. The gap means a distance from the superconducting coil bottom to the levitated object. The relationship is almost linear over the wide gap range.

becomes smaller in the range from 35 mm to 45 N. The change in attractive force is not so large with increasing distance. Although the persistent current of ≅ 70 A is applied to the magnetic suspension system, the energy loss for the bias current will be zero. This is very promising and amazing phenomenon.

4. Persistent current mode test

Persistent current mode test is performed using an electric circuit with a superconducting coil, a heater switch and a DC power supply as shown in Fig. 7. After the heater switch is turned OFF, a constant current is applied to the superconducting coil using the DC power supply as shown in Fig. 7(a) in order to make a persistent current. Then, the constant current flows through the superconducting coil from the DC power supply. After the switch is turned ON, the

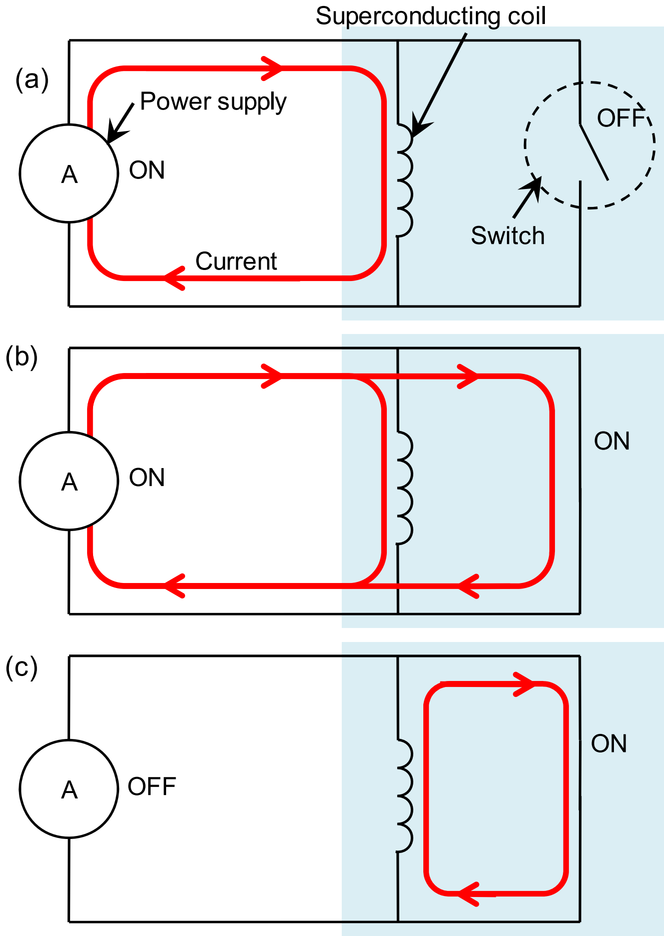


Fig.7 Process for the persistent current mode for the superconducting coil, where shows that (a) the current flows through only the superconducting coil because the switch is turned OFF, (b) the current flows through both the superconducting coil and the switch because the switch is turned ON, and (c) the current flows through only the superconducting coil, showing the persistent current mode.

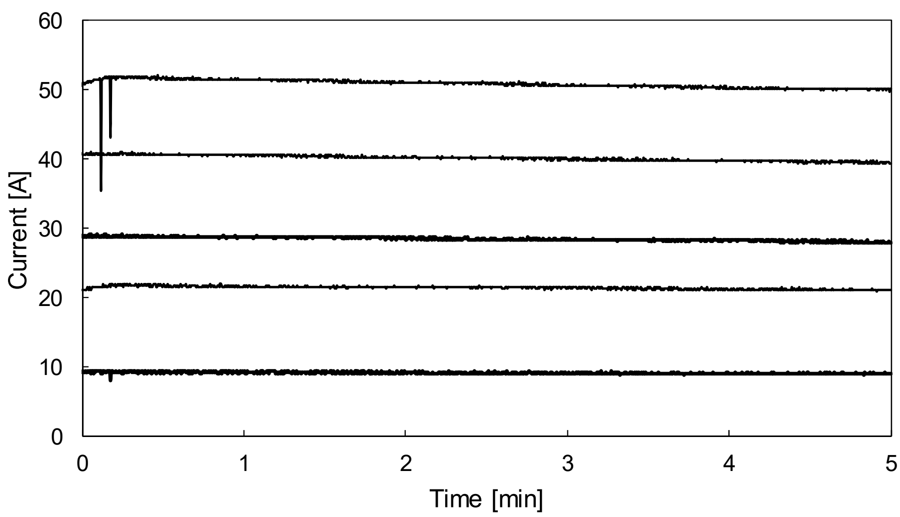


Fig.8 Relationship between persistent current and time for various initial currents of 10, 20, 30, 40 and 50A. Each persistent current continues to keep a constant current over a wide time range.

current from the DC power supply flows through the superconducting coil and the switch as shown in Fig. 7(b).

Moreover, after the power supply is turned OFF, the current flows through the superconducting coil and the switch instead of the DC power supply. Then, the persistent current mode continues to perform. In the experiment, magnetic flux density on the coil surface is measured in order to measure the persistent current.

Fig. 8 shows the relationship between the persistent current and the time for various initial currents of 10, 20, 30, 40 and 50A in the time range from 0 to 5 min. Each current continues to keep a constant current over a wide time range. That is, there is no current reduction after 5 min. Then, the energy loss at the solder joint of superconducting coil can be neglected.

Fig. 9 shows the relationship between the persistent current and the time for various initial currents of 60, 70, 80, 90 and 100A in the time range from 0 to 5.0 min. Each persistent current gradually decreases in the current range from 0 to 5.0 min. Especially the persistent currents for initial currents of 80, 90 and 100A rapidly decrease within 1.0 min. The reductions become larger within 1.0 min. as the initial currents become larger. This is because the large magnetic flux density in the center of the superconducting coil effects the current reduction from the initial current. However, each current reduction is small in the time range more than 2 min.

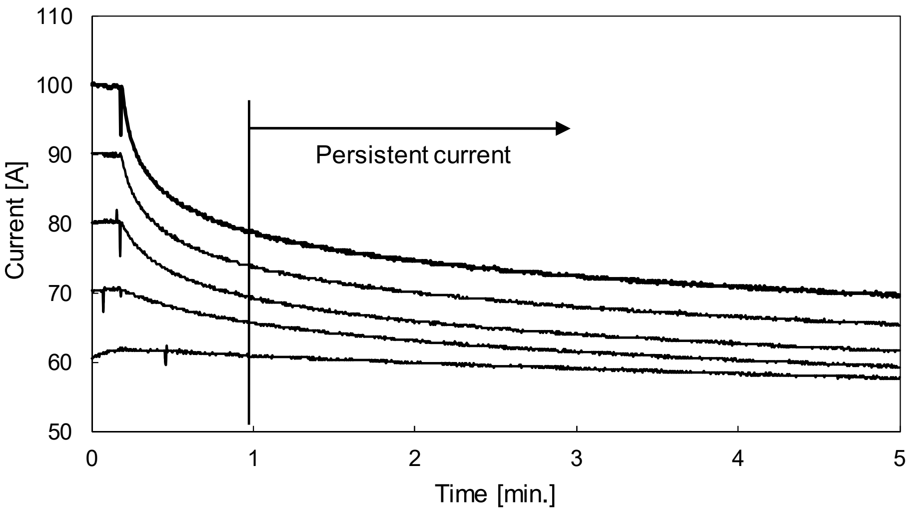


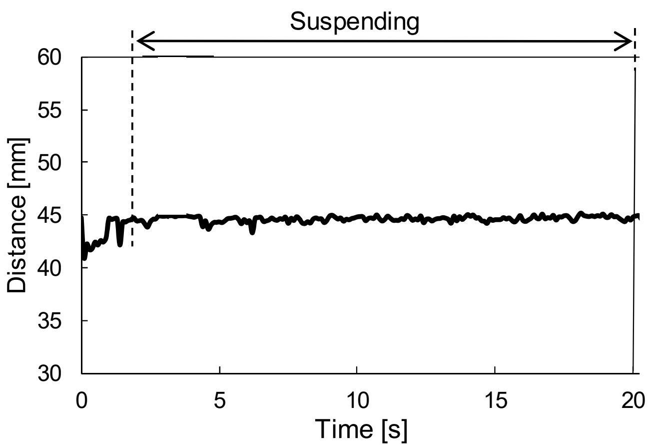
Fig.9 Relationship between persistent current and time for various initial currents of 60, 70, 80, 90 and 100A. Each persistent current gradually decreases in the current range from 0 to 5.0 min. Especially the persistent currents for initial currents of 80, 90 and 100A rapidly decrease within 1.0 min.

5. Suspending object

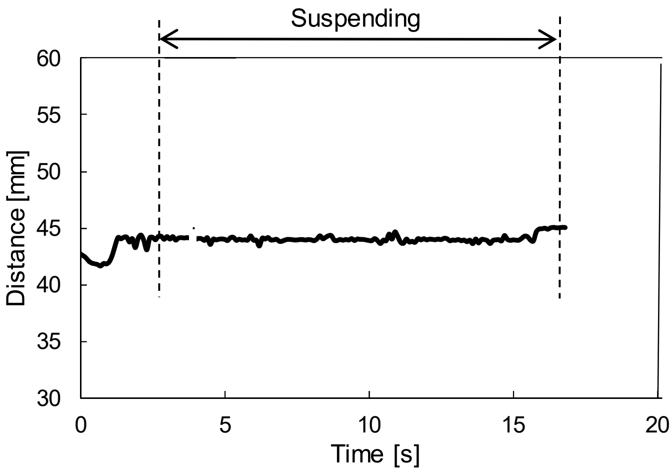
We try to magnetically suspend the object using power supply current and persistent current. In order to compare the suspended object, both DC power supply and persistent current are applied to the superconducting coil. Fig. 10 shows the experimental results for the magnetically suspended object, representing the distances using (a) DC power supply current and (b) persistent current. Fig. 10(a) shows that the magnetic suspension succeeds to start at ≈ 2 s and stops at ≈ 20 s. Then the magnetic suspension continues to keep for ≈ 18s. During the magnetic suspension, the vibration is observed and the amplitude is smaller than ≈ 2 mm. Fig. 10(b) shows that the magnetic suspension succeeds to start at ≈ 2 s and stops at ≈ 16 s. Then the magnetic suspension continues to keep for ≈ 14 s. During the magnetic suspension, the vibration is observed and the amplitude is smaller than ≈ 1 mm, which is rather smaller than that in Fig. 10(a). From these results, it is found that the magnetic suspension using persistent current is useful for wind tunnel test equipments.

6. Summary

Superconducting technique is applied to the magnetic suspension system. Persistent current in the superconducting coil and applied current to the copper coil are used for magnetically suspending object and controlling object,



(a) Power supply current



(b) Persistent current

Fig.10 Gap of suspended object using (a) power supply current and (b) persistent current. The bias current applied to the superconducting coil is 70 A.

respectively.

We try to magnetically suspend the object using the power supply current and the persistent current. In the case of using the DC power supply current, the magnetic suspension succeeds to continue for ≈ 18 s. The vibration amplitude is smaller than ≈ 2 mm. In the case of using the persistent current, the magnetic suspension succeeds to continue for ≈ 14 s. The vibration amplitude is smaller than ≈ 1 mm. From these results, it is found that the magnetic suspension using persistent current is useful for wind tunnel test equipments

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