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Active and Passive Damped Machining Tools for Vibration Control in Modern Manufacturing

Brij Bihari Singh[1], Mamta Kulkarni[2], Ajay Bansal[3]
Associate Professor, Assistant Professor
Department of Smart Manufacturing Systems
M.O.P. Vaishnav College for Women – Chennai, Tamil Nadu
Email:*Brijbihari06singh@yahoo.com[1], mamta77kulkarni@gmail.com[2],*
bansal_12ajay@rediffmail.com[3]

Abstract

Machining operations such as milling, turning and drilling often suffer from vibration problems which leads to poor surface finish, reduced tool life and lower machining accuracy. One of the major sources of vibration in machining is chatter, which is a self-excited vibration produced during the cutting process. To overcome these problems, damped machining tools are widely used in modern manufacturing industries. These tools reduce vibration through passive or active damping mechanisms. Passive damping tools mainly depend on mechanical elements such as viscoelastic materials, tuned mass dampers and friction systems to absorb vibration energy. On the other hand, active damping tools use sensors, actuators and control algorithms to detect and suppress vibrations in real time. This paper presents a review of active and passive damped machining tools used for vibration suppression in machining processes. The working principles, design approaches, advantages and limitations of both systems are discussed. Different types of damping technologies such as particle dampers, tuned mass dampers, piezoelectric actuators and magnetorheological dampers are also reviewed. A comparison between active and passive damping techniques is provided in terms of performance, cost and adaptability. The study indicates that passive damping tools are simple and reliable, while active damping systems offer higher vibration control capability in complex machining operations. The integration of smart sensors and intelligent control systems is expected to further improve machining stability in the future.

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INTRODUCTION

Machining is one of the most important manufacturing processes used for producing components with high dimensional accuracy and surface quality. Processes such as turning, milling, drilling and boring are widely used in industries including automotive, aerospace and heavy machinery manufacturing. However, during machining operations unwanted vibrations may occur due to cutting forces, machine flexibility and tool-workpiece interaction.

These vibrations can significantly affect machining performance. Excessive vibration leads to poor surface finish, dimensional inaccuracies, higher tool wear and sometimes even damage to machine tools. One of the most critical vibration problems in machining is chatter. Chatter is a self-excited vibration that occurs due to regenerative effects between the tool and workpiece.

In order to minimize these problems, several vibration control techniques have been developed. Among these techniques, damped machining tools are considered very effective. These tools are designed to reduce vibration by dissipating the vibration energy generated during cutting.

Damped machining tools are generally classified into two categories:

1. Passive damped machining tools
2. Active damped machining tools

Passive damping systems rely on mechanical or material properties to absorb vibrations without external energy input. In contrast, active damping systems use sensors, actuators and controllers to actively counteract vibrations.

This paper reviews the principles, design methods and applications of active and passive damped machining tools. The advantages and limitations of both approaches are also discussed.

MACHINING VIBRATIONS AND THEIR EFFECTS

During machining operations different types of dynamic forces are generated between the cutting tool and the workpiece. These forces are not always constant and may change continuously during cutting. Because of these variations, vibration may occur in the machine

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tool structure, spindle system, tool holder and even in the workpiece itself. Machining vibrations are very common in processes such as turning, milling, drilling and boring, especially when cutting at high speeds or when the tool overhang is large.

Several factors contribute to vibration in machining systems. One important factor is the variation in cutting forces which happens due to changes in chip thickness, material hardness or tool geometry. Another major reason is the flexibility of machine tool structures. Even though machine tools are designed to be rigid, some amount of structural flexibility always exist, and this flexibility allows vibrations to develop during cutting.

Other causes of machining vibration include imbalance in rotating components such as spindle and cutting tools, misalignment in machine parts, gear transmission errors and tool wear. As the tool becomes worn, the cutting forces become irregular and vibration may increase gradually. Environmental factors such as floor vibration and machine foundation conditions can also influence machining stability.

Machining vibrations are generally classified into three major categories: free vibrations, forced vibrations and self-excited vibrations. Each type of vibration has different causes and characteristics, and understanding these types is important for designing effective vibration control methods.

1. Free Vibrations

Free vibrations occur when a system is disturbed from its equilibrium position and then allowed to vibrate without any continuous external force acting on it. In this situation the system vibrates at its natural frequency, which depends on the mass and stiffness of the structure.

In machining systems, free vibrations may occur when there is a sudden disturbance such as tool engagement with the workpiece, accidental impact, or sudden stopping of the spindle. For example, when the cutting tool first touches the workpiece surface, the sudden contact can cause a temporary disturbance in the system and free vibration may start.

Another situation where free vibration may appear is during tool change or when the cutting process begins after machine idle condition. Once the disturbance is introduced, the system

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begins to vibrate naturally but the vibration gradually decreases with time due to internal damping present in the machine structure.

Although free vibrations normally decay after some time, if the machine structure has very low damping capacity, the vibration may last longer and affect the machining stability. Therefore machine tool designers try to increase structural damping through proper material selection and design modifications.

2. Forced Vibrations

Forced vibrations occur when a machine system is subjected to continuous external excitation. In machining operations these external forces are usually periodic in nature and may originate from several mechanical sources.

One common source of forced vibration is spindle rotation. If the spindle or cutting tool is not perfectly balanced, centrifugal forces will generate periodic excitation during rotation. This periodic force causes the system to vibrate at the same frequency as the excitation.

Gear transmission systems inside machine tools can also produce forced vibrations due to gear meshing errors or backlash. These small mechanical imperfections generate fluctuating forces which propagate through the machine structure.

Another source of forced vibration is the interrupted cutting process. For example, milling operations involve periodic engagement and disengagement of cutting teeth with the workpiece. Each tooth impact produces a small force impulse which may excite vibrations in the machine tool structure.

External environmental factors may also contribute to forced vibration. Nearby machines, floor vibrations, or foundation instability can transfer vibrations to the machining system. These disturbances may affect machining accuracy especially in precision manufacturing.

Forced vibrations usually occur at the frequency of the excitation force. If this excitation frequency becomes close to the natural frequency of the machine tool system, resonance may occur. Resonance greatly amplifies vibration amplitude and can cause severe problems in

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machining operations.

3. Self-Excited Vibrations (Chatter)

Self-excited vibration, commonly known as chatter, is considered the most harmful type of vibration in machining processes. Unlike free or forced vibration, chatter does not require periodic external excitation. Instead, it is generated due to the dynamic interaction between the cutting tool and the workpiece.

One of the most widely known mechanisms of chatter is regenerative chatter. In this phenomenon the cutting tool leaves a wavy surface on the workpiece during one revolution or pass. During the next cutting pass the tool encounters this uneven surface, causing variations in chip thickness. These variations produce fluctuating cutting forces which excite the machine structure.

As the process continues, the vibration grows and becomes self-sustaining. This regenerative mechanism leads to large amplitude oscillations between the tool and workpiece.

Chatter produces several undesirable effects in machining operations. It often generates loud noise during cutting, which is a clear indication of unstable machining conditions. The surface finish of the machined part becomes rough and wavy due to the vibration marks left by the tool.

In addition, chatter can significantly reduce tool life. The continuous vibration causes repeated impact loads on the cutting edge, leading to faster tool wear or even tool breakage in severe cases. Chatter also limits the maximum cutting depth and feed rate that can be used during machining, thereby reducing productivity.

Because of these serious effects, controlling chatter has become one of the major research topics in machining dynamics. Various methods such as damped tool holders, optimized cutting parameters and active vibration control systems are used to suppress chatter.

Effects of Machining Vibrations

Machining vibrations can influence the machining process in several negative ways. The most

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noticeable effect is poor surface finish. Vibrations cause the cutting tool to move irregularly relative to the workpiece, leaving visible marks and waviness on the machined surface.

Another important consequence is reduced dimensional accuracy. Vibrations may cause small deviations in tool position, resulting in errors in the final dimensions of the component. This problem is especially critical in precision manufacturing industries such as aerospace and medical device production.

Vibration also increases tool wear. When the cutting tool vibrates excessively, the contact between tool and workpiece becomes unstable. This produces fluctuating cutting forces which accelerate tool edge degradation. As a result the tool must be replaced more frequently, increasing production cost.

Machining efficiency is also affected by vibration problems. In unstable cutting conditions operators must reduce cutting speed, feed rate or depth of cut to maintain stability. This limitation reduces material removal rate and overall productivity.

In severe cases, excessive vibration may damage machine components such as spindle bearings, tool holders and drive mechanisms. Continuous vibration can also loosen machine fasteners and joints over time.

Because of all these issues, vibration control has become an important research area in modern machining technology. Advanced solutions such as passive damped tools, active vibration control systems and smart monitoring techniques are increasingly being developed to improve machining stability and productivity.

PASSIVE DAMPED MACHINING TOOLS

Passive damped machining tools are widely used in machining operations to reduce unwanted vibration and improve machining stability. These tools control vibration by using mechanical damping elements which absorb or dissipate the vibration energy produced during the cutting process. Unlike active damping systems, passive damping tools do not require sensors, controllers or external power supply. Because of this reason, they are simpler in design and easier to implement in industrial machining environments.

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During machining, dynamic cutting forces continuously act on the tool and workpiece. These forces can excite the natural frequencies of the machine tool system and produce vibration. Passive damping systems help to minimize this problem by increasing the energy dissipation capability of the tool structure. In other words, they convert vibration energy into other forms such as heat or distribute the energy within the system so that the vibration amplitude becomes smaller.

Passive damped tools are especially useful in operations where long tool overhang is required, such as boring, deep whole drilling and internal turning. In these operations the tool becomes more flexible and therefore more susceptible to vibration. By integrating damping mechanisms into the tool holder or boring bar, machining stability can be improved significantly.

Several passive damping techniques are commonly used in machining tools. These include viscoelastic damping, tuned mass dampers, particle damping and friction damping. Each technique has its own design principle, advantages and limitations.

1. Viscoelastic Damping

Viscoelastic damping is one of the most widely used passive damping methods in machining tools. Viscoelastic materials possess both elastic and viscous characteristics. Because of these properties, they can store mechanical energy like elastic materials and also dissipate energy like viscous fluids.

When a viscoelastic material is subjected to vibration, it undergoes cyclic deformation. During this deformation process, part of the mechanical energy is converted into heat due to internal friction within the material. This energy conversion reduces the vibration amplitude of the system.

In damped machining tools, viscoelastic layers are usually placed between different components of the tool holder. For example, a thin viscoelastic layer may be inserted between two metallic plates in the tool structure. When vibration occurs, the relative motion between the plates causes the viscoelastic material to deform and absorb energy.

Another approach is the use of sandwich structures where viscoelastic material is placed

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between two rigid metal layers. This design improves the damping capability while maintaining structural stiffness.

The main advantages of viscoelastic damping are its simple construction and relatively low cost. It does not require complicated design modifications and can be easily integrated into existing tool holders. Viscoelastic dampers also provide stable performance under normal machining conditions.

However, viscoelastic materials are sensitive to temperature changes. At high temperatures their mechanical properties may change and the damping performance may reduce. This limitation must be considered in high-speed or high-temperature machining processes.

2. Tuned Mass Dampers

A tuned mass damper (TMD) is another effective passive damping technique used in machining tools. This system consists of an additional mass attached to the main structure through a spring and damping element. The mass-spring system is tuned to the natural frequency of the machine tool or cutting system.

When vibration occurs in the main structure, the secondary mass begins to oscillate. Because the system is tuned to the same frequency, the motion of the secondary mass occurs in the opposite phase to the main vibration. This counteracting motion reduces the vibration amplitude of the main structure.

In machining applications tuned mass dampers are often integrated into boring bars or long tool holders. Long boring bars have relatively low stiffness and therefore they are prone to chatter during internal machining operations. By incorporating a tuned mass damper inside the boring bar, vibration can be effectively reduced.

The design of a tuned mass damper requires careful calculation of system parameters such as natural frequency, damping ratio and mass ratio. If the damper is not properly tuned, its effectiveness will be limited.

One advantage of tuned mass dampers is that they can significantly reduce vibration at a

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specific frequency. However, their performance is usually limited to a narrow frequency range. If machining conditions change and the excitation frequency shifts, the damper may become less effective.

Despite this limitation, tuned mass dampers remain widely used because of their reliability and simple mechanical design.

3. Particle Damping

Particle damping is a relatively simple and robust vibration control method. In this technique small particles such as steel balls, ceramic beads or metallic granules are enclosed inside a cavity within the tool holder or machine component.

When vibration occurs, the particles move freely inside the cavity and collide with each other as well as with the cavity walls. These repeated collisions dissipate vibration energy through impact and friction. As a result, the vibration amplitude of the system is reduced.

Particle damping is particularly effective because it works over a wide frequency range. Unlike tuned mass dampers which are effective only at specific frequencies, particle dampers can absorb vibration energy under varying machining conditions.

Another advantage is the simplicity of the design. The system does not require complex mechanical components, and the damping performance can be adjusted by changing particle size, material or filling ratio.

Particle dampers are also durable and can operate in harsh industrial environments without significant maintenance. They are often used in cutting tools, milling tool holders and boring bars where vibration control is required.

However, one disadvantage of particle damping is the increase in tool weight due to the additional particles. In some high-speed machining applications this added mass may influence dynamic behavior of the tool system. Therefore proper design consideration is necessary.

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4. Friction Damping

Friction damping is another passive technique used to control vibration in machining tools. This method relies on the dissipation of vibration energy through friction between contacting surfaces.

When two surfaces are pressed together and allowed to slide relative to each other, friction forces oppose the motion. During this sliding process mechanical energy is converted into heat, which reduces vibration amplitude.

In machining tools friction dampers are usually integrated into tool holders or boring bars using specially designed contact interfaces. For example, two metallic components may be clamped together under controlled pressure. When vibration occurs, slight relative motion between the components generates friction and dissipates energy.

The amount of damping produced by friction systems depends on several factors such as contact pressure, surface roughness and friction coefficient. By adjusting these parameters, the damping performance can be controlled. One advantage of friction damping is its simplicity and robustness. It does not require complex materials or mechanisms and can function reliably under various machining conditions.

However, friction dampers may experience wear over long periods of operation due to continuous sliding contact. This wear can change the friction characteristics and may reduce damping performance over time.

Overall, friction damping provides an economical and practical solution for vibration reduction in many machining applications.

Table 1. Common Passive Damping Techniques in Machining Tools

Damping Method	Working Principle	Advantages	Limitations
Viscoelastic damping	Energy absorbed through material deformation	Low cost, simple design	Temperature sensitive

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Damping Method	Working Principle	Advantages	Limitations
Tuned mass damper	Secondary mass counteracts vibration	Effective at specific frequency	Requires tuning
Particle damping	Energy dissipated by particle collisions	Wide frequency range	Increased tool weight
Friction damping	Sliding friction converts vibration energy	Simple and robust	Limited damping capacity

ACTIVE DAMPED MACHINING TOOLS

Active damped machining tools represent a more advanced approach for vibration control in machining processes. Unlike passive damping systems which rely only on mechanical elements, active damping systems use electronic components such as sensors, actuators and controllers to detect and suppress vibrations during the machining operation. These systems are capable of responding to vibration in real time, which makes them very effective for controlling complex and changing machining conditions.

In modern manufacturing environments where high precision and high productivity are required, active damping tools are becoming increasingly important. These tools can adapt to different cutting conditions and adjust their response accordingly. Because of this adaptability, active damping systems are particularly useful in high-speed machining, deep hole machining and operations involving long tool overhangs.

The basic working principle of active damping is based on sensing the vibration and generating a counteracting force that reduces or cancels the vibration. The system continuously monitors the dynamic behaviour of the tool and makes adjustments automatically.

The general structure of an active damping system usually includes four main components:

1. Sensors
2. Signal processing unit
3. Controller
4. Actuators

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Sensors are responsible for detecting vibrations in the machining system. Common sensors used include accelerometers, displacement sensors and force sensors. These sensors measure the vibration signals generated during cutting and convert them into electrical signals.

The signal processing unit then receives these signals and filters or amplifies them so that useful information can be extracted. This processed signal is then sent to the controller.

The controller is the central part of the active damping system. It analyzes the vibration data and determines the required control action. Based on the control algorithm, the controller sends commands to the actuators.

Actuators generate mechanical forces or displacements that counteract the detected vibration. In simple terms, the actuator produces a force in the opposite direction of the vibration so that the vibration amplitude becomes smaller.

Because this process occurs continuously during machining, the system can respond quickly to changes in cutting conditions. This real-time adjustment is the main advantage of active damping systems.

1. Piezoelectric Actuator Based Damping

Piezoelectric actuators are one of the most commonly used components in active vibration control systems. These actuators operate based on the piezoelectric effect, where certain materials produce mechanical deformation when an electric voltage is applied.

Piezoelectric materials such as lead zirconate titanate (PZT) are widely used because they can produce very small but precise movements. Even though the displacement produced is small, the response is extremely fast, which makes them suitable for vibration control applications.

In active machining tools, piezoelectric actuators are often integrated inside the tool holder, boring bar or spindle assembly. When the vibration sensor detects oscillations in the machining system, the controller sends an electrical signal to the piezoelectric actuator. The actuator then expands or contracts slightly, generating a force that opposes the vibration.

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Because this response occurs almost instantly, the vibration amplitude can be significantly reduced before it grows into chatter. This helps maintain stable cutting conditions.

Piezoelectric actuators offer several advantages in machining applications. They have very fast response time, allowing them to react quickly to vibration signals. They also provide high precision control because the actuator displacement can be controlled accurately by adjusting the applied voltage. Another benefit is their compact size, which allows them to be easily integrated into machining tools without major design modifications.

However, piezoelectric damping systems also have some limitations. The design of the control system can be quite complex, as it requires advanced control algorithms to determine the appropriate actuator response. In addition, piezoelectric materials may be sensitive to temperature changes and mechanical stress, which can affect their long-term reliability.

Despite these challenges, piezoelectric actuator systems are widely used in research and industrial applications for active vibration suppression.

2. Magnetorheological Dampers

Magnetorheological (MR) dampers are another type of active or semi-active damping technology used in machining systems. These dampers use a special type of fluid known as magnetorheological fluid. This fluid contains microscopic ferromagnetic particles suspended in a carrier liquid such as oil.

The unique property of MR fluid is that its viscosity changes when exposed to a magnetic field. In the absence of a magnetic field, the fluid behaves like a normal liquid. However, when a magnetic field is applied, the particles align themselves along the magnetic field lines, increasing the resistance to flow. As a result, the fluid becomes thicker and more resistant to motion.

This property allows the damping characteristics of the system to be adjusted by simply controlling the strength of the magnetic field. In an MR damper, an electromagnet is used to generate the magnetic field. By varying the electrical current supplied to the electromagnet, the viscosity of the MR fluid can be controlled.

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In machining tools, MR dampers can be integrated into tool holders or machine tool structures. When vibration occurs, the controller adjusts the magnetic field strength to increase or decrease the damping force as required. This adaptive behavior allows the system to respond effectively to different machining conditions.

One advantage of MR dampers is their ability to provide adjustable damping. Unlike passive damping systems which have fixed characteristics, MR dampers can modify their damping capacity depending on the vibration level. They also have relatively simple mechanical structures and can operate reliably under various working conditions.

However, MR damping systems require additional components such as electromagnets and control electronics, which increases system complexity and cost. There may also be some delay in the response due to the time required to change the magnetic field.

Even with these limitations, magnetorheological dampers are considered promising for advanced vibration control applications in machining.

3. Active Boring Bars

Active boring bars are specialized machining tools designed for internal machining operations such as deep hole boring. In these operations the tool often has a long overhang, which reduces its stiffness and makes it more susceptible to vibration and chatter.

To solve this problem, active boring bars integrate sensors, actuators and control electronics within the tool structure. These components work together to detect vibration and generate counteracting forces that stabilize the cutting process.

Typically, accelerometers or displacement sensors are mounted inside the boring bar to monitor vibration levels. The signals from these sensors are transmitted to a controller which analyzes the vibration characteristics. Based on this information, the controller sends commands to actuators installed inside the boring bar.

The actuators then produce small corrective movements that oppose the vibration. This active control helps maintain stable tool motion and reduces the possibility of chatter.

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Active boring bars offer several benefits in machining operations. They significantly improve surface finish by minimizing vibration marks on the machined surface. They also allow higher cutting speeds and larger depth of cut, which increases machining productivity.

Another advantage is improved tool life. Because the vibration level is reduced, the cutting tool experiences less mechanical stress and wear during machining.

However, active boring bars are more complex and expensive compared to conventional boring bars. The integration of sensors, actuators and electronic control systems requires careful design and maintenance. Despite this, their performance advantages make them valuable in high-precision and high-performance machining operations.

Table 2.Comparison of Passive and Active Damping Tools

Parameter	Passive Damping	Active Damping
Energy Requirement	No external energy	Requires power supply
Complexity	Simple	Complex
Adaptability	Limited	Highly adaptable
Cost	Lower	Higher
Maintenance	Low	Higher
Performance	Moderate	High vibration control

DESIGN CONSIDERATIONS FOR DAMPED TOOLS

When designing damped machining tools several factors must be considered.

1. Tool Geometry

The geometry of the tool holder affects stiffness and vibration characteristics. Proper design helps reduce vibration problems.

2. Material Selection

Materials with high damping capacity are preferred. Composite materials and viscoelastic layers are often used.

3. Natural Frequency

The natural frequency of the tool must be considered while designing damping systems. Tuned

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mass dampers must match the natural frequency of the tool system.

4. Integration of Sensors and Actuators

For active damping systems, sensors and actuators must be properly integrated to ensure accurate vibration detection and response.

APPLICATIONS OF DAMPED MACHINING TOOLS

Damped machining tools are widely used in different industrial applications.

1. Aerospace Industry

Aerospace components often require deep whole machining and thin wall structures. Damped tools help maintain machining stability and improve surface quality.

2. Automotive Manufacturing

In automotive production, high precision machining is required for engine components. Damped tools reduce vibration and increase productivity.

3. Heavy Machine Tools

Large workpieces and long tool overhangs often cause vibration problems. Damped boring bars and milling tools are used to improve machining stability.

FUTURE TRENDS IN DAMPED TOOL TECHNOLOGY

The development of smart manufacturing and Industry 4.0 has created new opportunities for advanced damped machining tools.

Future trends include:

- Integration of smart sensors in tool holders
- Use of artificial intelligence for vibration prediction
- Development of adaptive damping systems
- Integration with digital twin technology
- Use of advanced composite materials for better damping

These technologies will help improve machining accuracy and productivity.

CONCLUSION

Machining vibration is one of the major problems affecting productivity and product quality in manufacturing industries. Damped machining tools provide an effective solution to reduce these vibrations.

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Passive damping tools are simple, reliable and cost-effective. Techniques such as viscoelastic damping, tuned mass dampers and particle damping are widely used in industrial applications. Active damping systems provide higher performance by detecting and suppressing vibrations in real time. Technologies such as piezoelectric actuators and magnetorheological dampers allow adaptive vibration control.

Although active damping systems are more complex and expensive, they offer significant advantages in high precision machining operations.

Future developments in smart sensors, intelligent control algorithms and advanced materials will further enhance the performance of damped machining tools. Combining passive and active damping techniques may provide an effective approach for achieving high machining stability in modern manufacturing systems.

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