Lock-up Characteristics of the Hydraulic Snubber for Plant Piping Systems

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ABSTRACT

Nuclear power plant piping is required to accommodate thermal expansion during normal operation while maintaining structural integrity under dynamic loading conditions such as seismic events and external disturbances. Excessive restraint of thermal movement may induce additional stresses in piping, whereas insufficient restraint during abnormal conditions can lead to excessive displacement and potential structural damage. Hydraulic snubbers are therefore widely employed as passive mechanical devices that allow slow thermal displacement while restraining rapid dynamic motion of nuclear piping.

The performance of a hydraulic snubber is governed by its internal hydraulic snubber, particularly the locking mechanism that determines the transition from a flexible response to a rigid restraint. A key performance parameter is the lock-up velocity, which defines the velocity threshold at which the snubber begins to provide restraint. However, the internal flow characteristics and pressure distribution governing the lock-up velocity are not always well understood, often resulting in conservative design approaches and uncertainties in operational reliability.

In this study, a numerical investigation was conducted to analyze the internal hydraulic snubber of a hydraulic snubber using computational fluid dynamics (CFD). A detailed internal geometry was modeled, and steady-state flow analyses were performed under various piston velocities. The pressure distribution acting on the valve components was evaluated, and the resulting hydraulic forces were compared with the spring reaction force to identify the lock-up velocity based on force equilibrium.

The results show that the lock-up velocity of a hydraulic snubber can be predicted using CFD based on internal pressure distribution and force balance. The proposed analysis framework provides an effective approach for evaluating snubber performance and supports the design and assessment of hydraulic snubbers applied to nuclear piping. This study contributes to enhancing operational safety, long-term operation, and emergency preparedness of nuclear power plants by improving the understanding of passive vibration restraint devices.

Keywords: *Hydraulic snubber, Lockup-velocity, computational fluid dynamics (CFD)*

1 INTRODUCTION

In industrial environments, particularly within nuclear power plants, it is essential to ensure that piping systems are stored and maintained safely to prevent damage [1]. Nuclear power plant piping is required to accommodate thermal expansion during normal operation while simultaneously maintaining structural integrity under dynamic loading conditions, such as seismic events and external disturbances. If thermal movement is excessively restrained, it can induce additional stresses in the piping; conversely, insufficient restraint during abnormal conditions can lead to excessive displacement and potential structural damage.

Figure 1: Hydraulic snubber's shape

To address these challenges, hydraulic snubbers are widely employed as passive mechanical devices. These devices are designed to allow for slow thermal displacements while effectively restraining rapid dynamic motions of the piping. The performance of a hydraulic snubber is primarily governed by its internal hydraulic snubber, with the "lock-up velocity" being a critical performance parameter. This velocity defines the threshold at which the snubber transitions from a flexible response to a rigid restraint, as the valve cone closes due to pressure differences generated by the piston rod's movement.

Despite its importance, the internal flow characteristics and pressure distributions that govern lock-up velocity are not always well understood. This lack of detailed understanding often results in conservative design approaches and creates uncertainties regarding operational reliability. Therefore, it is crucial to analyze how the internal flow affects the valve components to evaluate the performance of these safety devices properly.[1]

In this study, a numerical investigation was conducted to analyze the internal hydraulic snubber of a hydraulic snubber using computational fluid dynamics (CFD). A detailed internal geometry was modeled to perform steady-state flow analyses under various piston velocities. By evaluating the pressure distribution acting on the valve components and comparing the resulting hydraulic forces with the spring reaction force, the lock-up velocity was identified based on force equilibrium. This research provides a verified analysis framework for evaluating how internal flow affects performance, contributing to the enhanced operational safety and long-term reliability of nuclear power plant piping systems.

2 THEORY AND SIMULATION

The operation of a hydraulic snubber is designed to protect piping systems by closing the valve cone when the piston rod's velocity exceeds a certain limit, which is triggered by the resulting internal pressure difference. In this study, a numerical analysis framework was established to predict this transition, known as the lock-up velocity.

2.1 THEORY

There are three reservoirs inside the snubber, and their locations are indicated in Fig. 2.

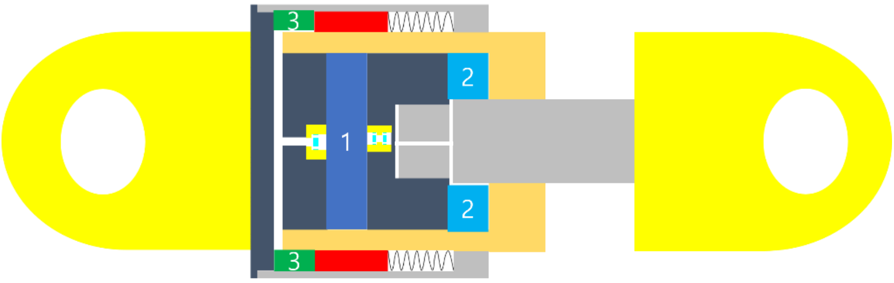

Figure 2: Location of the Reservoirs in the hydraulic snubber

When the piston rod of the snubber is compressed, the volume of Reservoir 1 decreases, causing the fluid to flow into Reservoirs 2 and 3. During extension, the fluid moves from Reservoir 2 back to Reservoir 1 as the volume of Reservoir 2 is reduced. The location of the valve, which assists in locking the piston's movement during emergency events, is shown in Fig. 3.

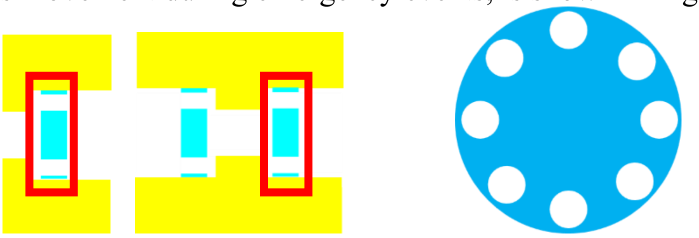

Figure 3: Valve cone's shape in the hydraulic snubber

Within this valve, there is a component referred to as the valve cone. The valve cone is positioned between a narrow flow path and a wide flow path, with a spring located in the narrow path to support the cone. Under normal operating conditions, the valve cone remains in an open state, allowing the fluid to pass through the flow path. However, in an emergency scenario where a rapid compression of the reservoir volume occurs, a large volume of flow is forced against the valve cone. This results in a pressure difference between the front and rear surfaces of the valve cone, which closes the previously open flow path and consequently halts the movement of the piston rod.

2.2 SIMULATION

In this study, the internal fluid domain of the hydraulic snubber was modeled, and flow analyses were performed for scenarios involving the compression and extension of the piston rod. The analysis for these conditions was conducted by utilizing two specific fluid domains: the domain between Reservoir 1 and Reservoir 3 and the domain between Reservoir 1 and Reservoir 2. The two flow field models created for this study are presented in Fig. 4.

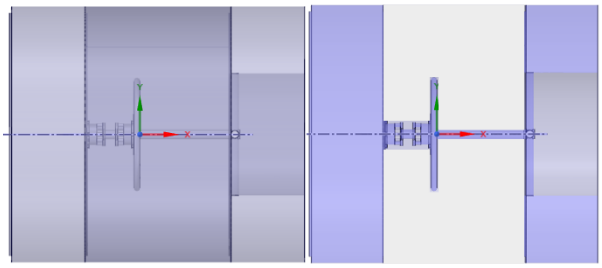

Figure 4: Fluid domain between Reservoir 1 to Reservoir 2

The lock-up phenomenon of a hydraulic snubber is fundamentally governed by the force equilibrium acting on the valve cone. As the piston rod moves during compression or extension, the internal fluid flow creates a pressure distribution across the valve components. Specifically, a pressure difference is generated between the front surface, where the flow first makes contact, and the rear surface supported by the spring. This pressure differential exerts a hydraulic force on the valve cone in the direction opposite to the spring's reaction force. The magnitude of this hydraulic force is calculated using the following equations:

$$\Delta P = P_{A_0} - P_{A_s} \tag{1}$$

$$F_{Valve\ cone} = \Delta P \times A_{Valve\ cone} \tag{2}$$

Let be the surface area of the valve cone where the fluid flow first makes contact during compression or extension, and be the area supported by the spring. As the piston rod moves, a pressure difference is generated between these two surfaces of the valve cone. The hydraulic force, which pushes the valve cone toward the spring, is determined by calculating the pressure difference across these areas and multiplying it by the valve cone's area. The lock-up velocity is then identified as the specific piston rod velocity at which the resulting hydraulic force, equals the spring reaction force, for each compression and extension scenario.

This analysis was conducted under steady-state conditions, with the inlet boundary condition defined as the flow rate corresponding to the piston rod's movement and the outlet boundary condition set as the internal pressure during the normal operation of the snubber.

2.2.1 PISTON ROD COMPRESSION

In the compression scenario of the piston rod, the valve cone located between Reservoir 1 and Reservoir 2, indicated in Figure 4, is the critical component that significantly influences the halting of the snubber. For the internal CFD analysis of the hydraulic snubber, Ansys Fluent R2025 was employed, using silicone oil AK350 as the working fluid. The density and viscosity of the working fluid are 0.97 g/cm³ and 350 mm²/s, respectively. The internal pressure during normal operation is 87,099.53 Pa, which serves as the Outlet condition in the simulation, while the Inlet condition is defined by the flow rate corresponding to the compression velocity of the piston rod. The positional information for the Inlet and Outlet conditions is illustrated in Figure 5, and the specific Inlet conditions according to the compression velocity are provided in Table 1.

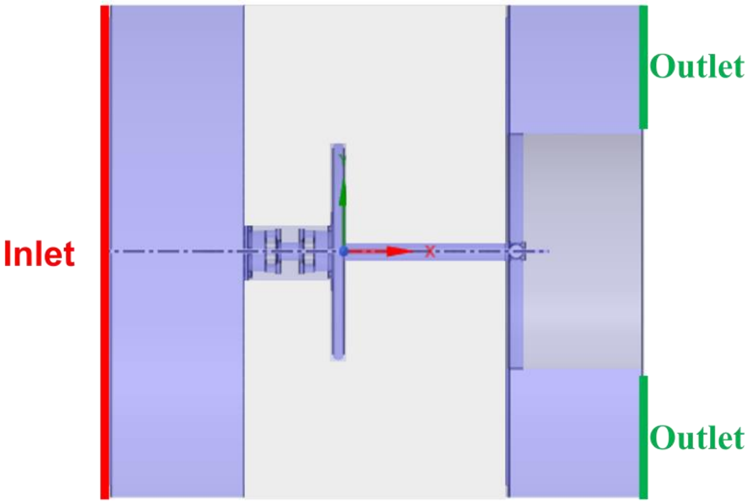

Figure 5: Inlet and outlet locations under compression conditions

Table 1 Inlet and outlet data under compression conditions

1 to 2 storage Push Velocity [mm/s]	Inlet boundary condition Mass Flow Rate [kg/s]
1	0.08741129
1.5	0.131116935
2	0.17482258
2.5	0.218528224
3	0.262233869
3.5	0.305939514
4	0.349645159
4.5	0.393350804
5	0.437056449
5.5	0.480762094
6	0.524467739

2.2.2 PISTON ROD TESION

In the tension scenario of the piston rod, the valve cone located between Reservoir 1 and Reservoir 2, indicated in Figure 4, is the critical component that significantly influences the halting of the snubber. For the internal CFD analysis of the hydraulic snubber, Ansys Fluent R2025 was employed, using silicone oil AK350 as the working fluid. The density and viscosity of the working fluid are 0.97 g/cm³ and 350 mm²/s, respectively. The internal pressure during normal operation is 87,099.53 Pa, which serves as the Outlet condition in the simulation, while the Inlet condition is defined by the flow rate corresponding to the tesion velocity of the piston rod. The positional information for the Inlet and Outlet conditions is illustrated in Figure 6, and the specific Inlet conditions according to the compression velocity are provided in Table 2.

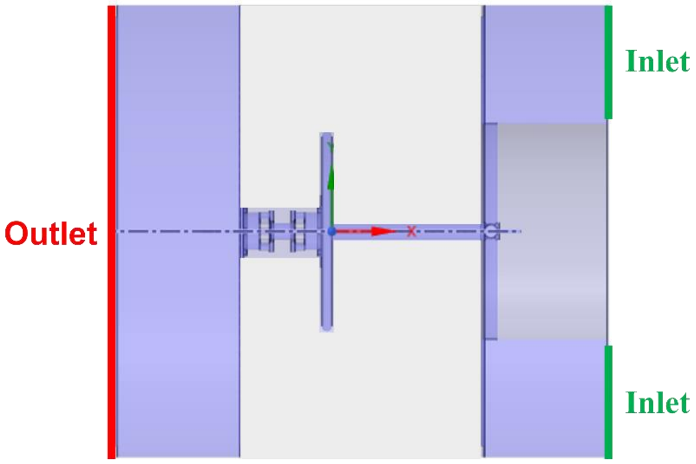

Figure 6: Inlet and outlet locations under tension conditions

Table 2 Inlet and outlet data under tension conditions

2 to 1 storage Pull velocity [mm/s]	Inlet boundary condition Mass Flow Rate [kg/s]
1	0.08741129
1.5	0.131116935
2	0.17482258
2.5	0.218528224
3	0.262233869
3.5	0.305939514
4	0.349645159
4.5	0.393350804
5	0.437056449
5.5	0.480762094
6	0.524467739

3 RESULT

The following are the results of the analysis conducted to identify the lock-up velocity of the hydraulic snubber during compression and extension. First, as illustrated in the graph of Figure 7, the results for the compression scenario show that the magnitude of the force acting on the valve cone increases progressively as the piston rod compression velocity rises from 1 mm/s to 3 mm/s. As the force on the valve cone gradually increases, it can be confirmed through the graph in Figure 7 that the magnitude of the valve cone force matches the spring reaction force of 23.7 N at a piston rod compression velocity between 2 mm/s and 3 mm/s.

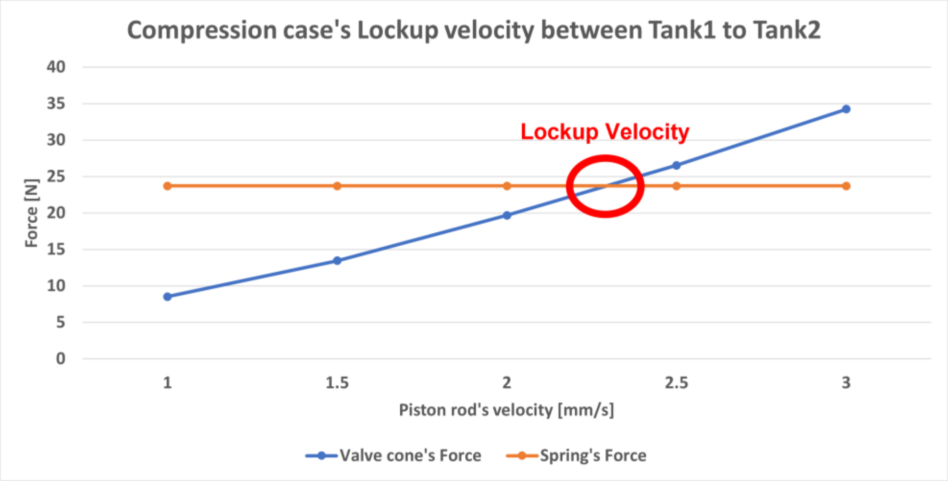

Figure 7: Compression case’s lockup velocity between Tank1 to Tank2

Regarding the analysis results for the tension scenario, as illustrated in the graph of Figure 8, it can be observed that the magnitude of the force acting on the valve cone increases progressively as the piston rod tension velocity rises from 1 mm/s to 3 mm/s. As the force on the valve cone gradually increases, it can be confirmed through the graph in Figure 8 that the magnitude of the valve cone force matches the spring reaction force of 23.7 N at a piston rod tension velocity between 2 mm/s and 2.5 mm/s.

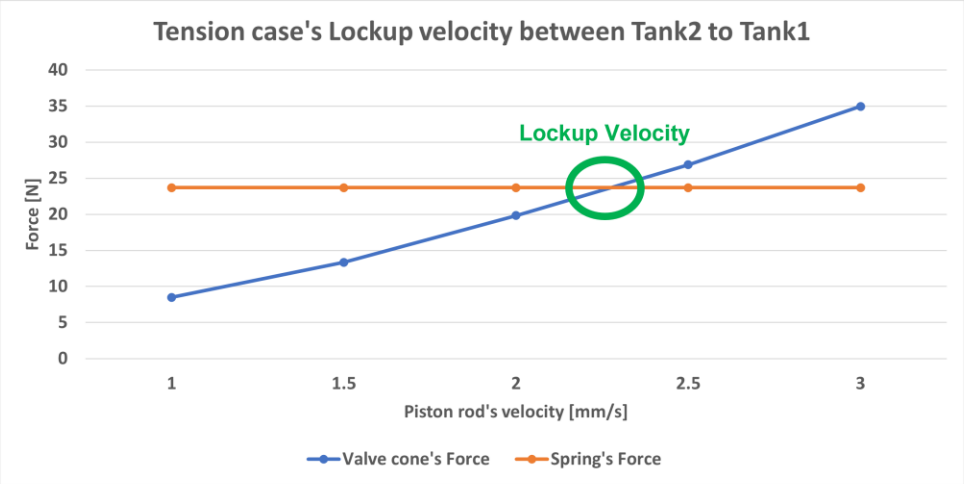

Figure 8: Tension case’s lockup velocity between Tank2 to Tank1

Experiments on the physical model of the hydraulic snubber analyzed in this study have not yet been conducted. As part of future research, the reliability of the numerical model will be established by comparing the experimental lock-up velocity results of the actual snubber model with the simulation results obtained in this study. Following the validation of the numerical model's reliability, further analyses will be performed to rapidly identify methods for achieving the target performance of the hydraulic snubber.

4 CONCLUSION

This study conducted a numerical investigation using computational fluid dynamics (CFD) to examine the internal flow of a hydraulic snubber and identify its lock-up velocity, a key performance indicator. Utilizing Ansys Fluent, the flow of silicone oil as the working fluid was modeled, and steady-state simulations were performed under various piston rod compression and extension velocities. The results confirmed that the snubber's lock-up phenomenon, which transitions the device from a flexible response to a rigid restraint, is determined by the force equilibrium acting on the valve cone. Specifically, the pressure difference generated between the front surface where the fluid first enters and the opposite surface supported by the spring creates a hydraulic force. When this force balances with the spring's reaction, the flow path is blocked, halting the piston's movement at a specific threshold.

Through the analysis, the pressure values acting on the valve cone were verified according to the piston rod's compression and extension velocities. The magnitude of the hydraulic force exerted on the valve cone was derived by calculating the pressure difference between both ends of the cone and multiplying it by its surface area. With the spring reaction force supporting the valve cone set at 23.7 N, the analysis results indicated that the piston rod velocity at which the hydraulic force matches the spring force—triggering the lock-up—lies between 2 mm/s and 3 mm/s. The proposed analysis framework offers an effective and verified methodology for the precise performance evaluation of passive vibration restraint devices. Ultimately, these findings are expected to contribute to ensuring the operational safety, long-term reliability, and structural integrity of nuclear power plant piping systems by enhancing the understanding of internal flow characteristics in safety-critical components.

5 REFRENCE

[1] Analysis of A Velocity and Pressure Drop of The Hydraulic Coupler using Computational Fluid Dynamics (CFD), Dae-Bin Song, Gyeong-Yun Baek, J. Korean Soc. Mech. Technol, 24(4): 677~683, 2022

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