Elucidating the mechanism of hydraulic noise using computational fluid dynamics

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Abstract

Hydraulic system noise has often been addressed experimentally through trial and error. In this study, computational fluid dynamics (CFD) was applied to analyze hydraulic noise, enabling the reproduction of valve regulating pressure behavior and detailed examination of the flow field. The results revealed a mechanism where air entrained in the oil expands and compresses within the circuit, generating noise—a phenomenon that is challenging to investigate through experimental methods alone. This paper details the mechanisms underlying the noise and proposes effective countermeasures.

1. Introduction

NVH (Noise, Vibration, and Harshness) is a critical consideration in transmission development. In particular, hydraulic system noise poses significant challenges due to the complexity of the system and the large number of components involved, making pinpointing the noise source and understanding its underlying mechanism difficult. Consequently, trial-and-error experiments are often employed, such as alternating operating conditions to identify noise-inducing factors or recombining components to determine their contribution to the noise.

In recent years, however, the adoption of computational fluid dynamics (CFD) has become essential in hydraulic system design. CFD enables precise and quantitative evaluations, facilitating decision-making in addressing hydraulic issues.

This paper presents a case study in which CFD was applied to analyze noise in hydraulic transmission systems with the following objectives: (1) to identify the noise source, (2) to estimate the underlying mechanism, and (3) to verify the proposed mechanism. The focus was on noise generated immediately after shifting from N to D range while the engine was running.

2. Narrowing down the issues through experiments

2.1 Narrowing down the noise source

Figure 1 shows a schematic diagram of the hydraulic system of an automatic transmission (hereinafter referred to as “AT”). In an AT, the oil in the oil pan is pumped to various components using an oil pump, where the control valves regulate the pressure and flow of the distributed oil. A pressure regulator valve is located upstream of the control valve. In the system in which noise is generated, a lubrication regulator valve is located immediately downstream of the pressure regulator valve, and the hydraulic pressure in the lubrication circuit is controlled.

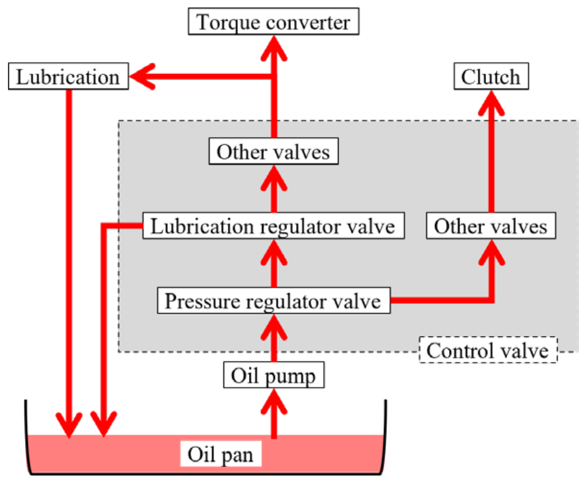

Fig. 1 Schematic diagram of hydraulic system

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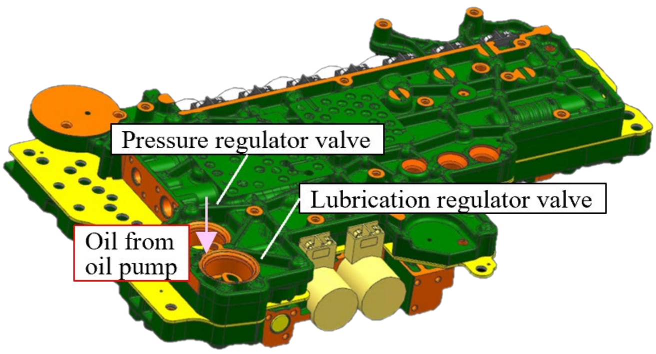
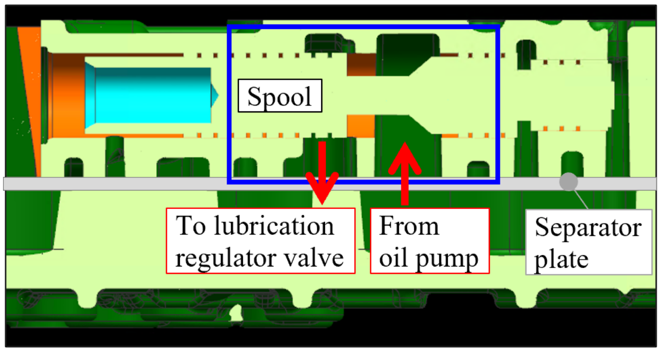
Initially, noise-generation sites were roughly identified through experimentation. Given the timing of the noise occurrence, only the pressure regulator valve and the lubrication regulator valve were active during the shift operation. This allowed the noise source to be narrowed down to one of these two valves. However, as shown in Fig. 2(a), the proximity of the two valves makes conclusively determining the noise source impossible using experimental noise observation alone.



(a) Location of pressure regulator valve and lubrication regulator valve in control valve

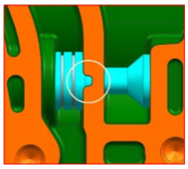
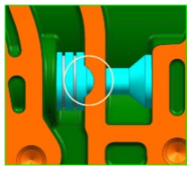
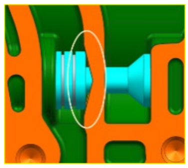


(b) Cross section of pressure regulator valve

Fig. 2 Control valve and pressure regulator valve

To address this, the notch shape of the pressure regulator valve is modified, as detailed in Table 1, and the resulting noise levels are observed. The notch shapes, viewed from below in the blue frame of Fig. 2(b), include cylindrical and triangular designs. The results revealed that both alternative shapes reduced the noise level compared to the original design. However, the possibility remained that altering the shape of the pressure regulator valve could influence the behavior of the lubrication regulator valve. Consequently, definitively identifying the noise source was still not possible.

Table 1 Noise reduction by notch shape

Original shape	Cylindrical notch	Triangular notch
		
Noise occurred	Noise reduced	Noise reduced

2.2 Narrowing down the causes of hydraulic noise

From experience, three possible factors cause hydraulic noise.

Factor 1: Vibration of components due to the oscillation of hydraulic pressure

Factor 2: Vibration of components due to pressure fluctuations during vortex release

Factor 3: Pressure fluctuations due to air expansion/compression

First, to evaluate Factor 1, the line pressure was experimentally measured during the noise generation using the original notch shape (Fig. 3). The results showed that the hydraulic pressure did not oscillate during, before, or after the noise generation. This finding ruled out Factor 1 as a potential cause of the noise. However, Factors 2 and 3 could not be investigated through this experiment alone, necessitating further refinement and analysis.

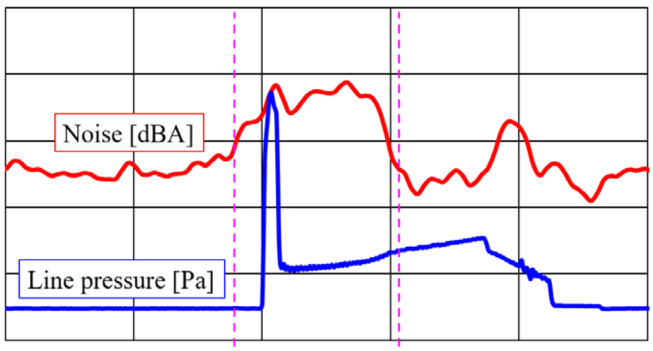


Fig. 3 Noise and line pressure over time

3. Elucidating hydraulic noise mechanism using computational fluid dynamics

3.1 Noise source identification

CFD was applied to address the experimental limitations in identifying the sources and causes of the noise. First, to narrow down the focal area, a noise-generating valve was identified.

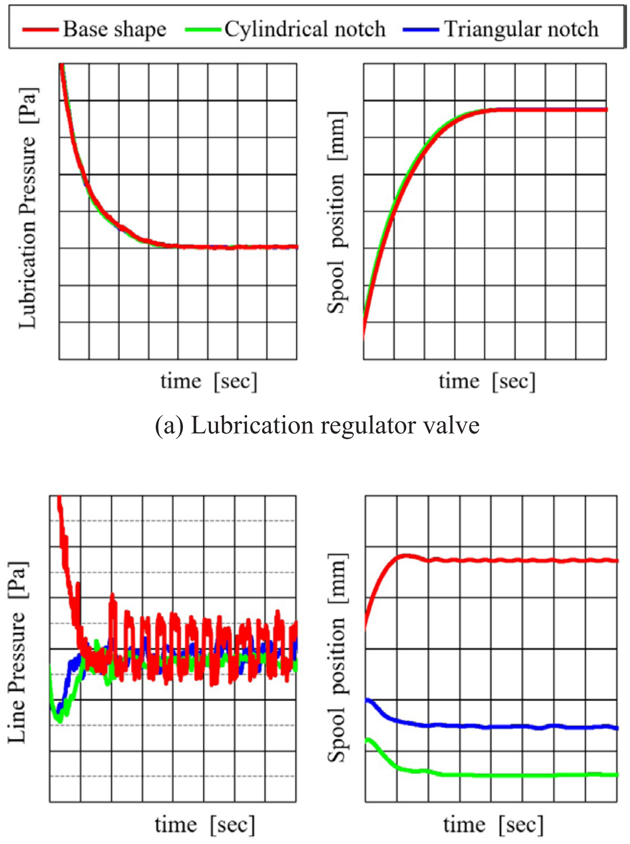
As shown in Table 1, the noise volume changes with modifications to the notch shape. This suggests that either the pressure regulator valve, the lubrication regulator valve, or both had altered their regulating states. To confirm the pressure-regulating states for the three notch configurations, simulations were conducted using STAR-CCM+, a general-purpose thermal-fluid dynamics solver. The hydraulic circuits associated with both the pressure regulator and lubrication regulator valves were analyzed. The motion of each spool was solved using the fourth-order Runge-Kutta method, while a sliding mesh and morphing (mesh movement and expansion/contraction) were employed to reproduce the spool motion accurately.

Figure 4 illustrates the time variations in output pressure and spool position for the pressure regulator and lubrication regulator valves. The analysis revealed no significant changes in the output pressure or spool position for the lubrication regulator valve with the notch modifications. In contrast, the pressure regulator valve exhibited substantial changes in both output pressure and spool position. These results confirm that the pressure regulator valve, rather than the lubrication regulator valve, is the noise source.

3.2 Estimation of mechanisms

3.2.1 Cause analysis: Vortex release

When an orifice or another aperture is present in the circuit, periodic vortices may form downstream of the orifice, and the pressure fluctuations caused by the vortex release may induce vibrations in the components, resulting in noise generation (Factor 2). Figure 5 shows a typical example of flow analysis through an orifice, where the colors represent the pressure distribution. The oil flowed from top to bottom, with positive and negative pressures aligned downstream of the orifice, indicating that vortices were periodically released at this location. The separator plate could vibrate due to these pressure fluctuations, generating noise.



(a) Lubrication regulator valve

(b) Pressure regulator valve

Fig. 4 Pressure and spool position over time

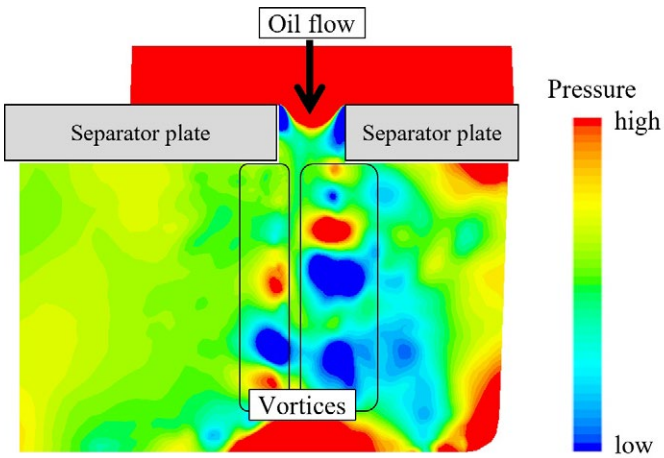


Fig. 5 Pressure distribution in orifice flow

In Figure 6, it can be observed whether a similar phenomenon occurs in the pressure-regulator valve. This shows the pressure distribution during pressure regulation. No periodic release of vortices is evident near the separator plate (in the solid-line enclosure), which has the potential to vibrate. This indicates that the noise is not caused by vortex emission.

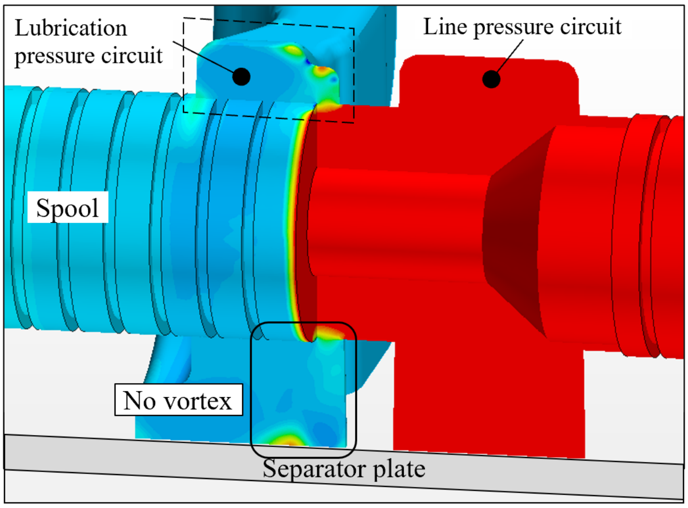


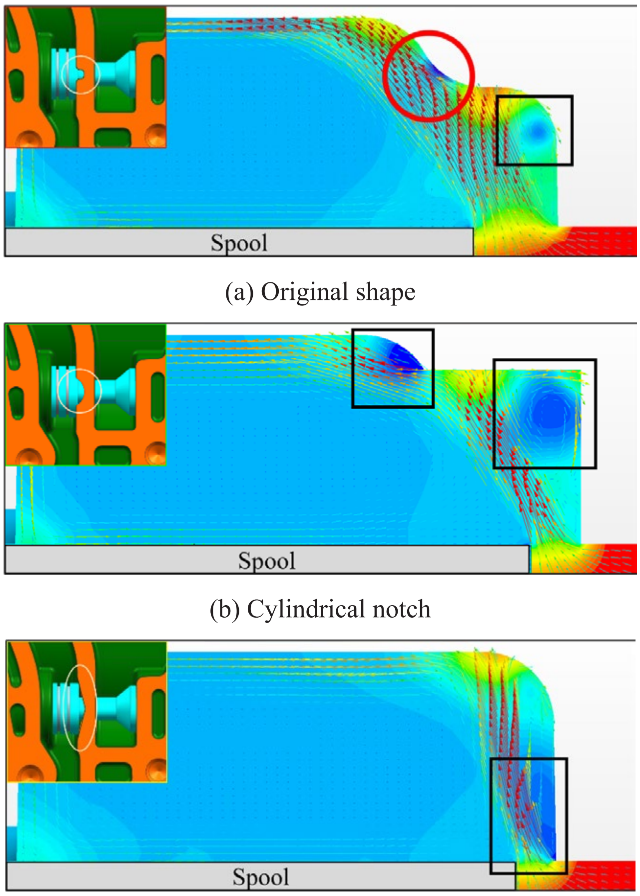
Fig.6 Pressure distribution around pressure regulator valve

3.2.2 Cause analysis: Air expansion/compression

Another possible cause is pressure fluctuations due to air expansion and compression. The oil circulating in the transmission contains fine air bubbles, only a few percent by volume at atmospheric pressure. Strange noises reported in the past were caused by air expansion when drained from the hydraulic circuit to the oil pan, i.e., at atmospheric pressure. However, hydraulic pressure was applied to all connected circuits at the pressure regulator valve, identified as the noise source in this study. Therefore, the critical question is whether air expansion and compression are sufficient to generate noise in such a pressurized state.

The pressure distribution on the opposite side of the separator plate (inside the dashed-line enclosure in Fig. 6) was investigated for the original, cylindrical, and triangular notch shapes, all of which exhibited different noise volumes (Fig. 7).

For all notch shapes, a strong low-pressure region, responsible for air expansion, is identified. Simultaneously, two types of air inflators became evident. The first, enclosed by black rectangles, is formed by a vortex created due to flow separation, where pressure decreases at the vortex center. In such cases, the vortex fluctuation significantly affects the noise volume. However, in the present configuration, the position of the separation is fixed at the notch opening or step edge, and the position of vortex formation does not change significantly with the notch shape.



(a) Original shape

(b) Cylindrical notch

(c) Triangular notch

Fig.7 Pressure distribution and velocity vector at lubrication pressure port of pressure regulator valve

Therefore, even if the air expands because of the low pressure, the pressure fluctuation is considered relatively small, and the noise volume is considered low.

In contrast, in the area circled in red, the flow path narrows due to the step, causing an increase in flow speed and resulting in a low-pressure region. This mechanism is similar to cavitation in a hydrofoil[1], where bubbles in a jet stream expand rapidly in the low-pressure zone and compress rapidly after passing through it. This rapid compression of bubbles probably produces significant pressure fluctuations akin to cavitation, generating noise. The low-pressure zone associated with this mechanism is present only for the original notch shape and is absent in the other two shapes, where noise is reduced. This suggests that the primary cause of the noise is the rapid expansion and compression of air due to the localized increase in flow speed and the corresponding decrease in pressure caused by flow condensation.

4. Verification of mechanism

The estimated noise mechanism was next verified by experiments and computational fluid dynamics. Because noise is thought to be caused by the expansion of air in the oil due to a pressure drop, an increase in the lubrication pressure, which is the surrounding pressure, is expected to suppress the pressure drop in the low-pressure region and, in turn, reduce the noise.

Figure 8 shows the CFD results when the lubrication pressure increased for the original notch shape. Compared with Fig. 7(a), the decrease in the step pressure indicated by the red circle is suppressed by increasing the lubrication pressure.

Figure 9 shows the calculated results for the relationship between the lubrication pressure and step pressure. Evidently, a near-linear correlation exists between the lubrication pressure and step pressure.

In addition, the magnitude of the noise was measured with increasing lubrication pressure (Fig. 10). Clearly, the noise decreased as the lubrication pressure increased. This result presents the following clear correlation: “noise decreases as step pressure increases,” and validates the assumed mechanism. Simultaneously, the noise problem was solved by increasing the lubrication pressure during the N-D shift.

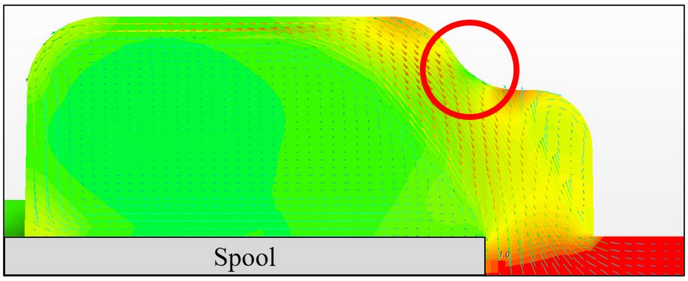


Fig. 8 Pressure distribution and velocity vector at lubrication pressure port of pressure regulator valve - lubrication pressure is higher than original

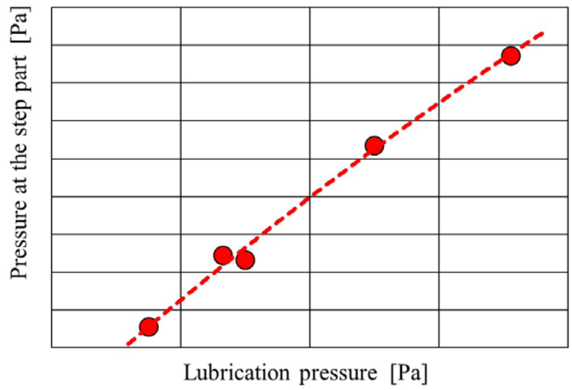


Fig. 9 Relationship between lubrication pressure and step part pressure

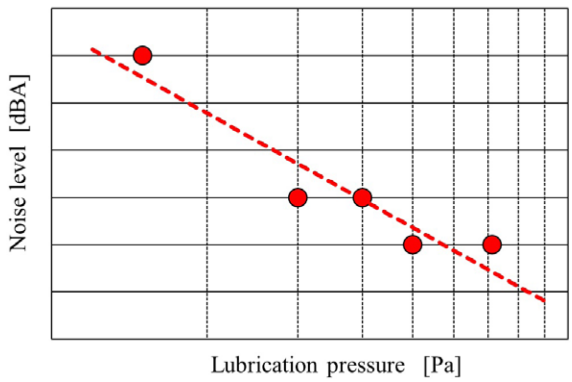


Fig. 10 Relationship between lubrication pressure and noise level

5. Summary

The following results were obtained by applying CFD to hydraulic system noise, which previously required considerable time and cost to solve through trial-and-error experiments:

① The sound source can be easily identified by applying a regulating pressure analysis that enables quantitative evaluation.

② By visualizing phenomena that could not be observed in experiments, the mechanism of noise generation could be estimated simply by examining the CFD results, even if the mechanism had never been experienced before.

③ Because a localized pressure drop in the hydraulic circuit was found to be the cause of noise, the mechanism behind reduced noise could be verified using a relatively simple method of increasing the lubrication pressure.

These outcomes cannot be obtained using only an experimental approach, highlighting the usefulness of CFD.

6. References

(1) Kazuo Suzuki, Takafumi Kawamura, Noriyuki Sasaki: Chapter 6 Cavitation, in Hull Resistance and Propulsion, Ship Marine Engineering Series 2, Seizando Publishing, (2012), pp.211-240

(2) Masaru Shimada: "Elucidation of Noise Mechanism of Hydraulic System Using CFD," Proceedings of the 2024 Spring Meeting (Spring), pp. 1-4, 20245156, Reprinted with permission from the Society of Automotive Engineers of Japan, Inc.

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