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STUDY ON THE INSERTION LOSS CHARACTERISTICS OF SIDE BRANCH RESONATOR IN HYDRAULIC LINE

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ABSTRACT

A quarter wavelength side branch resonator has been widely used as a reactive type silencer to attenuate pressure pulsation in hydraulic circuit. The structure of this conventional silencer is very simple and therefore it is a useful device in terms of cost efficiency. However, it is also known as a rather narrow frequency banded resonator that only attenuates the odd order harmonics of the pressure pulsation.

In this study, the attenuation performance of side branch resonator in the hydraulic line is examined numerically by changing the parameters such as the insertion location of side branch and the length of connecting pipe between the side branch and termination load of circuits. The level of attenuation is accessed by insertion loss which is defined as the ratio of overall amplitude harmonics of pressure pulsation with and without the side branch. The paper describes the fundamental principle of side branch and the mathematical model of insertion loss characteristics. Some calculation results for the insertion loss characteristics are carried out to show the influence of even order harmonics and the interaction of pump, termination load and all pulsation propagation characteristics of the circuit including side branch.

KEY WORDS

Hydraulic Silencer, Insertion Loss, Pressure Pulsation, Side Branch

NOMENCLATURE

a : Transfer matrix of upstream line of side branch
b : Transfer matrix of downstream line of side branch
c : Speed of sound
IL : Insertion loss
IL_{OA}: Insertion loss using overall pressure pulsation
L : Length of side branch
L_2 : Length between pump and side branch
L_3 : Length between side branch and termination load
P : Pressure pulsation
P' : Pressure pulsation with side branch
P_d : Discharge mean pressure
Q_m : Mean flow rate
Q_s : Source flow pulsation
r : Radius of pipe
s : Laplace operator
T : Transfer matrix of side branch
TL : Transmission loss
W_i : Incident energy of pulsation into silencer
W_i : Transmitted energy of pulsation through silencer
Z_2 : Impedance of downstream line of side branch
Z_c : Characteristics impedance of side branch pipe
$Z_{c.c}$: Characteristics impedance of connecting pipe
Z_T : Load impedance
Z_s : Source impedance of pump

θ : Pump rotational angle
ν : Kinematic viscosity of working fluid
$\xi(s)$: Coefficient which express viscosity resistance
ρ : Density of working fluid

INTRODUCTION

It is well known that all positive displacement pumps generate a flow pulsation, which interacts with the system to produce pressure pulsation. This pressure pulsations are usually the primary source of system noise because they are very easily transmitted throughout the entire system and then excite the mechanical vibrations that generate audible noise. The pressure pulsation is a periodic function of time with a fundamental frequency and higher harmonics. Consequently, if the pump runs relatively constant in the operation cycle such as in a hydraulic excavator, an injection molding machine, etc., the harmonic frequencies of pressure pulsation would be almost constant. For this kind of hydraulic systems, a side branch resonator is often used as a hydraulic silencer [1]. This silencer is only a branch pipe installed in the main flow line. Since its simple structure and low cost, it is known as one of the most effective way to reduce pressure pulsation for an application which operates at a constant speed.

In this report, the attenuation performance of side branch resonator in the hydraulic line is investigated numerically by changing the circuit parameters such as the insertion location of the side branch resonator and the length of connecting pipe between the side branch resonator and termination load of circuits. The level of attenuation is accessed by the insertion loss which is defined as the ratio of the overall amplitude harmonics of pressure pulsation with and without the side branch resonator. The paper describes the fundamental principle of side branch resonator and the mathematical model of insertion loss characteristics. Some calculation results for the insertion loss characteristics are carried out to show the influence of even order harmonics and the interaction of pump, termination load and all pulsation propagation characteristics of the circuit including side branch resonator.

SIDE BRANCH RESONATOR

Figure 1 shows the basic structure of a side branch resonator and the schematic diagram of its resonance mode. Since the termination end of side branch resonator is closed and the connection end to the main line is opened, the standing waves of pressure and flow pulsation become the resonance mode at frequencies correspond to a quarter wave length and its odd number

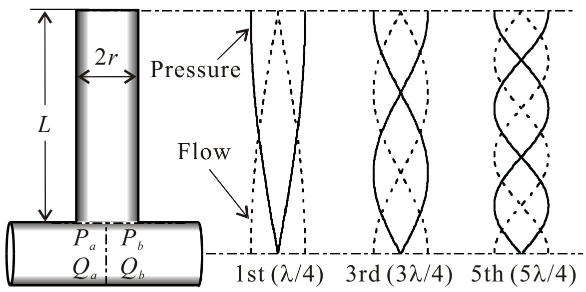


Figure 1 Basic structure of side branch resonator and its resonance mode

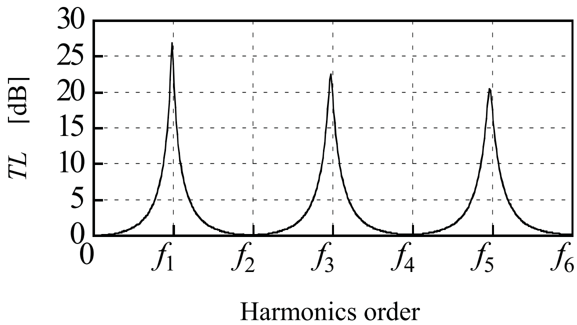


Figure 2 Transmission loss of side branch resonator

multiples. Therefore the pressure pulsation can be attenuated around these frequencies.

The wave propagation characteristics of side branch resonator can be expressed by Eq. (1) as a four pole Laplace transfer matrix, provided that the boundary of inlet and outlet is set by the dotted line in Fig.1.

$$\begin{bmatrix} P_a \\ Q_a \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \dfrac{1}{Z_c(s)}\tanh\left\{\dfrac{\xi(s)s}{c}L\right\} & 1 \end{bmatrix} \begin{bmatrix} P_b \\ Q_b \end{bmatrix} \tag{1}$$

where P_a and Q_a , P_b and Q_b are pressure and flow pulsation at inlet and outlet of side branch resonator respectively. Z_c is the characteristic impedance of the branch pipe and $\xi(s)$ is the complex coefficient for unsteady laminar viscous friction effect [2].

$$Z_c(s) = \frac{\rho c \xi(s)}{\pi r^2} \tag{2}$$

$$\xi(s) \cong 1 + \sqrt{\frac{\nu}{r^2 s}} + \frac{\nu}{r^2 s} \tag{3}$$

Once the transfer matrix of the side branch resonator is obtained, the transmission loss can be also derived from this transfer matrix [3]. Transmission loss is a measure which express an attenuation performance of hydraulic silence itself and is defined as the ratio of the incident energy W_i to the transmitted energy W_t when there are no reflections in the downstream line of silencer. It is often used to compare the relative performance of silencers. With the transfer matrix elements of a silencer $T_{1.1} \sim T_{2.2}$, the transmission loss is described as the following equation.

$$TL = 10\log_{10}\left(\frac{W_i}{W_t}\right)$$

$$= 20\log_{10}\frac{1}{2}\left|\left\{T_{1.1} + \frac{1}{Z_{c.c}(s)}T_{1.2} + Z_{c.c}(s)T_{2.1} + T_{2.2}\right\}\right| \quad (4)$$

where $Z_{c.c}$ is the characteristic impedance of the connecting pipe (main line) of the side branch resonator. Moreover, the transmission loss of the side branch resonator can be expressed in Eq. (5) by substituting Eq. (1) for Eq. (4).

$$TL = 20\log_{10}\frac{1}{2}\left|\left[2 + \frac{Z_{c.c}(s)}{Z_c(s)}\tanh\left\{\frac{\xi(s)s}{c}L\right\}\right]\right| \quad (5)$$

Figure 2 shows the example transmission loss characteristics of the side branch resonator. It can be seen from this figure that the attenuation peaks are appeared at frequency f_1 that correspond to a quarter wave length resonance mode and its odd multiple frequencies. This indicates that the side branch resonator is only able to attenuate the harmonic components of pressure pulsation around these frequencies.

INSERTION LOSS CHARACTERISTICS

The insertion loss is the difference in amplitude of pressure pulsations in the downstream line with and without a silencer and it is the final criteria that shows how effective a silencer is.

$$IL = 20\log_{10}\frac{P}{P'} \quad (6)$$

where P and P' are the pressure pulsation without and with the silencer.
However the insertion loss involves the complex interaction of the wave propagation characteristics in both the upstream line including the pump pulsation source and the downstream line including the load as well as the silencer itself. Consequently, all these pulsation characteristics of hydraulic circuit have to be

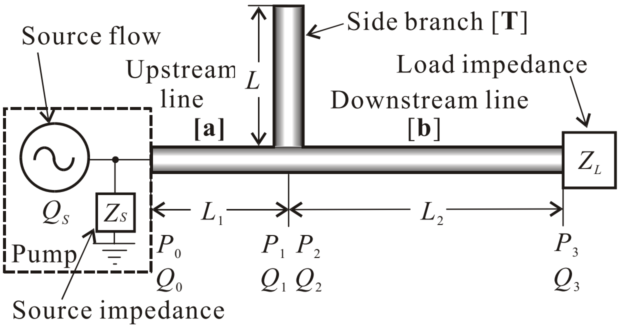


Figure 3 Hydraulic circuit represented by pulsation characteristics

taken into account of the insertion loss calculation. Figure 3 shows the test hydraulic circuit which is parameterized by the pulsation characteristics. Firstly the pulsation source of pump is characterized by the source flow Q_s and source impedance Z_s. In this pump model, the flow pulsation Q_s is generated at an exit of discharge port in parallel with the source impedance Z_s. the pulsation wave propagation characteristics for the upstream line, downstream line and side branch resonator are expressed by the transfer matrix [**T**], [**a**], [**b**]. The load impedance Z_L characterizes the termination of hydraulic circuit such as a control valve.
Pressure pulsation at any point of the circuit can be expressed by these pulsation characteristics. For example, P_3, where is the possible highest pulsation point because it is just in front of the load, is obtained by the following equation [4].

$$P_3 = \frac{Z_L Z_S Q_S}{(b_{1.1}Z_L + b_{1.2})\{(a_{1.1} + a_{1.2}Z_S) + (a_{1.2} + a_{2.2}Z_S)\}} \quad (7)$$

where $a_{1.1} \sim a_{2.2}$ and $b_{1.1} \sim b_{2.2}$ are the elements of transfer matrix [**a**] and [**b**]. The pressure pulsation at the same point with the side branch resonator P_3' is also expressed by Eq. (8).

$$P_3' = Z_2 Z_L Z_S Q_S / [(b_{1.1}Z_L + b_{1.2})\{(a_{1.1} + a_{2.1}Z_S)$$
$$(T_{1.1}Z_2 + T_{1.2}) + (a_{1.2} + a_{2.2}Z_S)(T_{2.1}Z_2 + T_{2.2})\}] \quad (8)$$

where $T_{1.1} \sim T_{2.2}$ are the transfer matrix element of [**T**] and Z_2 is the entry impedance of the downstream line of side branch resonator, which is shown as follows

$$Z_2 = \frac{P_2}{Q_2} = \frac{b_{1.1}Z_L + b_{1.2}}{b_{2.1}Z_L + b_{2.2}} \quad (9)$$

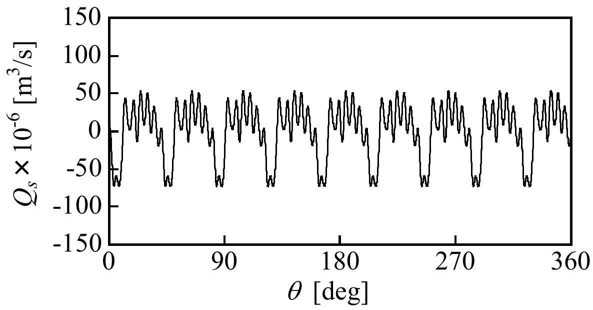
It must be borne in mind that these equations for

insertion loss refer to only one frequency because they are all dependent on frequency.
As is already shown in Fig.2, the side branch resonator is a relatively narrow banded hydraulic silencer which has the attenuation ability around the fundamental frequency and its odd harmonic frequencies. Therefore, the insertion loss for these interested harmonic frequencies (the fundamental and odd harmonics only) have been focused to evaluate the performance of the side branch resonator. In this report, all harmonic components of pressure pulsation including even number harmonics are taken into consideration of the side branch resonator performance so that a real attenuation performance (i.e. amplitude of a peak to peak pulsation) can be assessed. In order to achieve this, an overall value of pressure pulsation is used in the insertion loss instead of each harmonic component in Eq. (6). The overall pressure pulsation is defined as the square root of the sum of the squares of all the harmonic components and the insertion loss using the overall pressure pulsation can be described in Eq. (10).

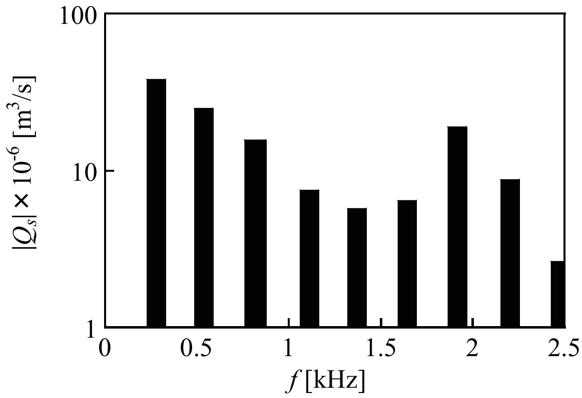
$$IL_{OL} = 20\log_{10}\frac{\sqrt{\sum|P|^2}}{\sqrt{\sum|P'|^2}} \qquad (10)$$

SIMULATION AND CONSIDERATIONS

Simulation condition
For the hydraulic circuit such as a construction machine, the side branch resonator is typically installed close to a pump discharge port. Then the flexible hoses or steel pipes are the elements that connect the pump to the termination element such as a control valve of actuators. In this report, the insertion loss characteristics of side branch resonator for this hydraulic circuit are examined by the simulation work. The basic configuration of the hydraulic circuit is already shown in Fig.3. In this simulation, an axial piston pump (displacement: 23 cc/rev., number of piston: 9) is selected as the pulsation source and the steel pipe is used for the pipe element to connect a loading valve to the pump. The side branch resonator is also considered to be the same steel pipe made.
The pulsation source characteristics of the pump used in this simulation are shown in Fig.4 and Fig.5. These results are obtained experimentally from the '2 pressure / 2 systems' method [5]. The running condition of the simulation is set to as follows. The rotational speed of the pump is 1833 min^{-1} (the fundamental frequency of the pump induced pressure pulsation becomes 275 Hz) and the discharge mean pressure P_d is 10MPa. Figure 4 (a) and (b) show the time history waveforms of the source flow pulsation Q_s and its amplitude spectra. It should be noted that this source flow pulsation Q_s is



(a) Time history waveforms



(b) Amplitude spectra

Figure 4 Source flow pulsation of pump

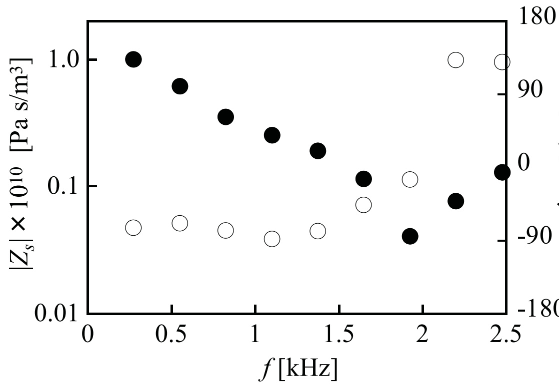


Figure 5 Source impedance of pump

generated at the exit of the pump discharge port. Figure 5 shows the source impedance of the pump. This value characterizes the internal (from the discharge port exit) impedance of the pump. It can be seen that an anti-resonance corresponding to the quarter-wavelength mode of the discharge port, at which the amplitude of the source impedance reaches a minimum and the phase

angle switches from -90 to +90, is apparent at around 2.0 kHz.
In this report, the insertion loss characteristics of the side branch resonator is investigated by changing the insertion location of side branch resonator and the length of the connecting element between the side branch resonator and the termination of circuit. For this reason, the steel pipe are chosen to the connecting elements since the wave propagation characteristics of the pipe is well known theoretically [6]. Provided that the flow in the steel pipe is the two-dimensional, laminar, viscous and compressible, the transfer matrix of the upstream line [**a**] can be described by the following equation.

$$[\mathbf{a}] = \begin{bmatrix} \cosh\left\{\dfrac{\xi(s)s}{c}L_2\right\} & Z_{c.c}(s)\sinh\left\{\dfrac{\xi(s)s}{c}L_2\right\} \\ \dfrac{\sinh\left\{\dfrac{\xi(s)s}{c}L_2\right\}}{Z_{c.c}(s)} & \cosh\left\{\dfrac{\xi(s)s}{c}L_2\right\} \end{bmatrix} \quad (11)$$

The transfer matrix of the downstream line [**b**] can be also expressed in the same equation by substituting L_3 for L_2. The insertion location of the side branch resonator is determined by the length of the upstream line L_2. Generally the side branch resonator is installed near the pump exit or sometimes in the pump casing. In this work, the pipe length L_2 is varied from 0 to 0.5m. The length of the pipe, which connects the termination load element to the pump and is obtained as the sum of L_2 and L_3, is varied from 0.5 to 2.0m so as to examine how this line affects the attenuation performance of side branch resonator as well as the influence of insertion position. The radius of the pipe including the side branch resonator is r=10.5 mm.
Then the termination load of the circuit is assumed to be a load valve, which can be modeled as a resistive impedance load. The load impedance becomes

$$Z_L = \frac{2P_d}{Q_m} \quad (12)$$

where Q_m is the mean flow rate ($Q_m=7.03\times10^{-4}\mathrm{m^3/s}$). The working fluid in this simulation is the ISO VG32 hydraulic oil (ρ=875kg/m^3, $\nu=3.2\times10^{-6}$Pas, c=1400m/s).

Simulation results
Since the fundamental frequency of the pump induced pressure pulsation is 275Hz, the length of the side branch resonator is designed to L=1.27m in order to match the quarter wavelength resonance mode to the fundamental frequency. For this condition, the insertion loss using the overall pressure pulsation in Eq. (9) was calculated with varying two circuit parameters. Figure 6

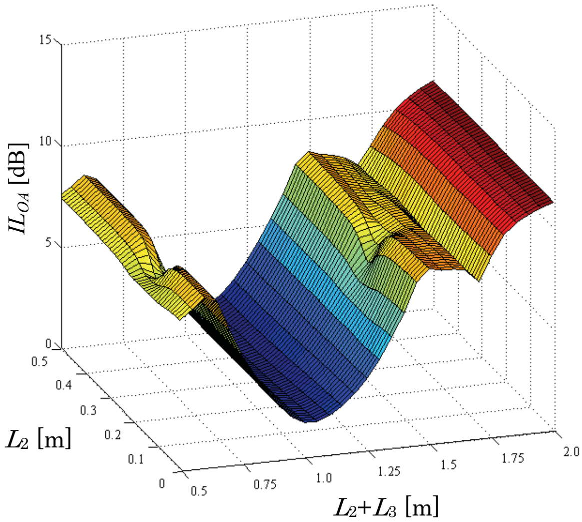


Figure 6 Insertion loss characteristics

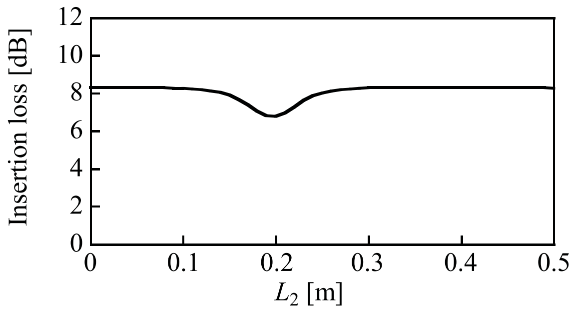


Figure 7 Insertion loss versus insertion location (L_2+L_3=0.6m)

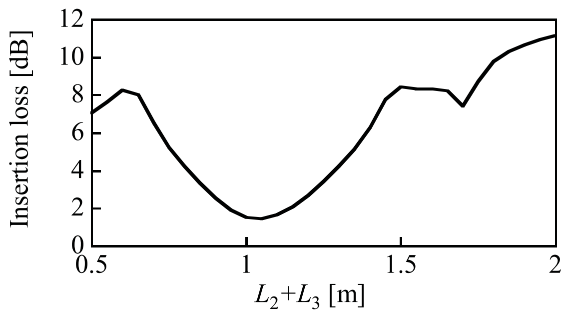


Figure 8 Insertion loss versus length of circuit (L_2=0.1m)

shows the insertion loss characteristics of the side branch resonator. The axis of L_2 is the insertion location of the side branch resonator from the pump exit and the axis of L_2+L_3 is correspond to the total circuit length where is from the pump to the termination loading valve. The typical characteristics of these insertion loss are extracted for each parameter and shown in Fig.7 and Fig.8. From these results, it is obvious that the insertion loss characteristics using the overall pressure pulsation is significantly dependent on the length of the main circuit line, while it is little affected by the insertion location. It can be seen from Fig.8 that the difference in the insertion loss at the length of the circuit L_2+ L_3=1m and L_2+L_3=1.5m becomes 6dB. This insertion loss characteristics is mainly due to the standing wave of pressure pulsation generated inside the circuit line.

Figure 9 explains how the standing wave contributes. This figure shows the amplitude of pressure pulsation for the fundamental and the second order harmonic frequency with the side branch resonator. This is so called the standing wave of pressure pulsation. The side branch resonator is installed at the pump exit (L_2=0m) and two circuit length conditions, L_3=1m and L_3=2m, are shown in this figure. It is clear that pressure pulsation of the fundamental frequency component is well attenuated by the side branch resonator for both circuit length conditions. On the contrary, the second order harmonic component remains the same as it is without the side branch resonator. The important thing is that the amplitude of this harmonic frequency is much bigger than the attenuated fundamental harmonic component as well as other harmonic components and this contributes dominantly to the insertion loss using the overall pressure pulsation. This is a reason why the insertion loss characteristics is not affected by the insertion location of the side branch resonator in this report. The harmonic component attenuated by the side branch resonator is rather negligible although the insertion location has a effect on the attenuation performance of the fundamental and the odd harmonic components. It should be mentioned that the insertion location should be close to the pump exit, because these is no attenuation effect on the upstream line of the side branch resonator.

If the second order harmonic frequency is close to the resonance mode of the circuit including the side branch resonator, this harmonic component become large as shown in Fig.9 at L_3=1m. Therefore the insertion loss performance become worse. It can be said that design of the circuit length is very important for the use of the side branch resonator, which is the narrow banded hydraulic silencer.

CONCLUSION

In this report, the attenuation performance of side branch resonator in the hydraulic line is investigated numerically by the insertion loss using the overall pressure pulsation. The following knowledge can be drawn from this work.

The insertion loss defined as the overall pressure pulsation with and without the hydraulic silencer is suitable to access the narrow banded hydraulic silencer such as a side branch resonator because it can express all the harmonic components at once.

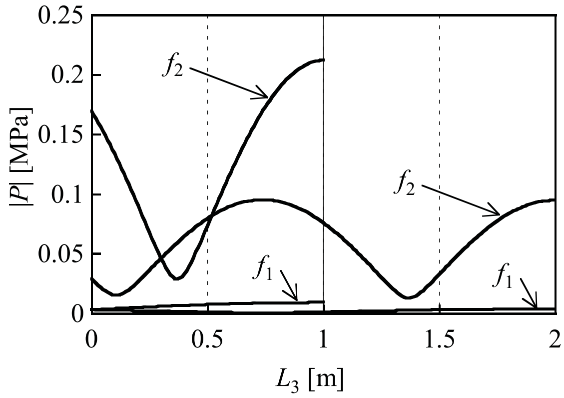


Figure 9 Standing wave of pressure pulsation for fundamental and 2nd order harmonic component (L_2=0.0 m, f_1=275 Hz)

The even order harmonic components of pressure pulsation can be dominant since the odd order harmonic components are attenuated by the side branch resonator. Therefore the length of the connecting pipe between the pump and the load should be carefully designed in order to avoid the system resonance mode at the even number harmonic frequencies.

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