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An Analyzing Method of Pressure Wave Propagation in Hydraulic Transmission Line for Automotive Power Steering System

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자동차 동력조향용 유압 관로계에서의 압력 맥동 전파 특성 해석법

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국문 요약

이 연구에서는 고압 호스에서의 파속 데이터에 기초한 새로운 맥동류 해석법을 제안한다. 이어서, 저자가 제안한 고압 호스에서의 파속 측정법인 「3개 압력 변환기를 갖는 폐쇄 출구 도관법」을 사용하여 자동차 동력 조향 장치용 레조네이터 호스 각 부품에서의 파속 데이터를 계측해둔다. 최종적으로 몇 개의 연구 대상 레조네이터 호스에 대한 압력 맥동 감쇠 특성 실험 및 시뮬레이션을 수행한다. 그 결과로부터, 제안한 압력 맥동 전파 특성 해석법의 타당성을 검증한다.

주제어 : 맥동류, 파동 전파 속도, 레조네이터 호스

Ⅰ. Introduction

To reduce fluidborne noise in automotive HPS(hydraulic power steering) systems, a "resonator hose" originally proposed by Klees(Klees, 1967) is usually used in power steering high pressure lines. The resonator consists of hydraulic hose(s) and flexible metal pipe(s) called "spiral pipe" or "tuning cable". The resonator hose is fabricated by placing spiral pipe(s) inside sections of hose coaxially.

In this study, the author suggests a new method for analyzing pulsating flow in hose based on wave speed data measured through a preliminary test. Using a wave speed measuring method proposed by the author(Lee and Kang, 2006), wave speed data in each component of the object resonator hoses are measured through preliminary experiments. Finally, with several object resonator hoses, pressure attenuation characteristics are investigated by experiments and simulations. For the simulation, the measured wave speed data are utilized. The simulation results are compared with the experimental ones, and the validity of the suggested method for analyzing pulsating flow in resonator hose is confirmed.

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Ⅱ. Methods for analyzing pulsating flow in hoses

1. Former researches on hose modeling

Among the former researches on the analyses of wave propagation characteristics in hoses(viscoelastic fluid pipes), Yu and Kojima's works(Yu and Kojima, 1995) are understood to be an extensive research considering almost all the meaningful physical items in hoses. In the view point of applicability of the model(Yu and Kojima, 1995) to practical hoses, however, the followings could be pointed out; (1) As physical parameters for the model(Yu and Kojima, 1995), the components of normal strain in the circumferential and longitudinal directions are measured by strain gauges. But these kinds of measurements could be performed with comparatively stiff hoses for industrial uses(not for automobile power steering uses). (2) The retardation and relaxation time constant of a hose wall are evaluated by an optimization method with the measured transfer matrix parameters of hose. This procedure would require very precise measurements and computing process. (3) The model is applied to hoses for comparatively high pressure (over 21 MPa) uses, where physical parameters of hoses remain constants over wide range of frequency. Conclusively speaking, it seems that the model(Yu and Kojima, 1995) requires a quite complex procedure to apply it to practical hoses. And also, the model seems not appropriate to soft hoses like ones for automobile power steering uses.

2. Suggestion of a new method for analyzing pulsating flow in hoses (viscoelastic pipes)

The Laplace transformed variables of pressure and flowrate in arbitrary two positions #1 and #2 on a hose will be denoted as (P_1, Q_1) and (P_2, Q_2). The relation between the variables is represented as following transfer matrix equation, on the assumption that the hose wall does not encounter the dynamic longitudinal deformation due to a longitudinal resonance of a hose.

$$\begin{bmatrix} P_1 \\ Q_1 \end{bmatrix} = \begin{bmatrix} \cosh(\lambda_h l) & Z_h \sinh(\lambda_h l) \\ \frac{1}{Z_h} \sinh(\lambda_h l) & \cosh(\lambda_h l) \end{bmatrix} \begin{bmatrix} P_2 \\ Q_2 \end{bmatrix} \quad (1)$$

where, l is hose length between position #1 and #2, and Z_h is the characteristic impedance of a hose and described as

$$Z_h = \frac{\rho \lambda_h {c_h}^2}{A_h\, s} \quad (2)$$

In equation (2), ρ is the density of fluid in a hose, c_h is wave speed in a hose, A_h is cross-sectional area of a hose, and s is Laplace operator and λ_h is wave propagation coefficient of a hose. λ_h in equations (1) and (2) is written as equation (3) with an approximate form(Brown, 1962).

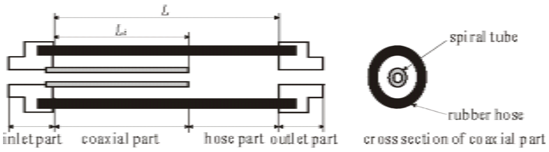
$$\lambda_h \approx \frac{s}{c_h}\left[1+\left(\frac{\nu}{R^2 s}\right)^{0.5}+\left(\frac{\nu}{R^2 s}\right)+\frac{7}{8}\left(\frac{\nu}{R^2 s}\right)^{1.5}\right] \quad (3)$$

where, ν is kinematic viscosity of fluid, R is radius of a hose(pipe). As we see in equations (1)~(3), if $c_h[=f(s)]$ is known, the pulsation transfer characteristics in a hose can be computed.

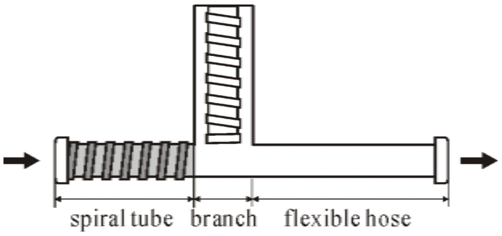
In this study, the author suggest a new method of pulsating flow analyzing in hoses not by using any mathematical models on wave speed, but by using frequency series wave speed data measured through a preliminary test.

Ⅲ. The resonator hose

For the resonator hose shown in [Fig. 1] and [Fig. 2,] the following transfer matrix equation can be written



[Fig. 1] Structure of the resonator hose



[Fig. 2] Equivalent pipe model for the resonator hose shown in Fig. 1

$$\begin{bmatrix} P_1 \\ Q_1 \end{bmatrix} = T \begin{bmatrix} P_2 \\ Q_2 \end{bmatrix} \qquad (4)$$

The total transfer matrix T in equation (4) is denoted as equation (5), that is the multiplication of the transfer matrices of the spiral pipe part, the branch part(the coaxial part) and hose part.

$$T = M_{spiral} \cdot M_{branch} \cdot M_{hose} \qquad (5)$$

In equation (5), $M_{hose}$is the same matrix as shown in the right side of equation (1). M_{spiral} has the same in the form of matrix as M_{hose}, except that λ_h in M_{hose} is replaced by λ. M_{branch}, the transfer matrix of the branch part(= the coaxial part, see [Fig. 1] is described as

$$M_{branch} = \begin{bmatrix} 1 & 0 \\ 1/Z_{cb}\tan(\lambda_b l_b) & 1 \end{bmatrix} \qquad (6)$$

where λ_b, Z_{cb}(Washio & Konishi, 1984) are described as

$$\lambda_b = \frac{s}{c_b}\left(1 + \frac{1}{(1-m)z} + \frac{1}{2(1-m)^2 z^2} - \frac{1-2m+m^2}{8m(1-m)^3 z^3} \right) \qquad (7)$$

$$Z_{cb} = \frac{\rho\, {c_b}^2}{A_b s}\lambda_b \qquad (8)$$

where c_b : wave speed in a coaxial hose, l_b: length of a coaxial hose, $m = r_2/r_1$, r_2 : inside radius of a hose, r_1: outside radius of spiral pipe, $z = \sqrt{r_2^2\ s/\nu}$.

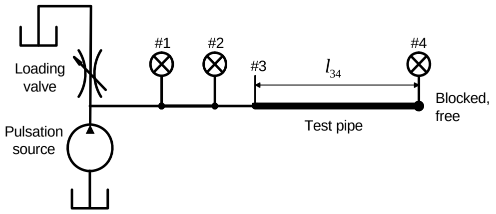
In equation (7) and (8), unknown parameters are wave speed data in each components of the resonator hose. Therefore, if we have wave speed data in the components, we can analyse the pulsation flow characteristics in the resonator hose.

Ⅳ. Preliminary experiments using the resonator hose

In this paper, the author suggested a new method to analyse pulsating flow in hoses by using frequency series wave speed data in hoses. This concept to analyse pulsating flow in hoses will be applied to the other components like the spiral pipe part and the coaxial part in the resonator hose(refer to [Fig. 4]), to analyse the pulsating flow in the whole resonator hose. To use this method to analyse pulsating flow in resonator hose, in this section, wave speed data in each component of the resonator hose shall be evaluated through preliminary experiments.

1. Wave speed in a metal pipe and a hose

The pump for pulsating flow generation in the test system was a variable displacement type piston pump with 9 pistons, 14 $\mathrm{cm}^3/\mathrm{rev}$ capacity, and a regulator having constant pressure control function. The test was carried out by recording pressure signals for about 10 seconds while the pump was driven with continuously varying speed from 0 to 3000 rpm by a servo motor. The measured pressure signals were FFT transformed and utilized to obtain frequency series wave speed data by using the wave speed evaluating process(Lee & Kang, 2006).

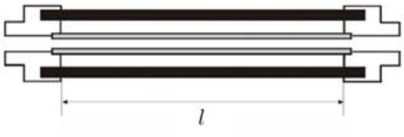


[Fig. 3] “Closed-outlet-conduit with three transducers“ method(Lee & Kang, 2006)

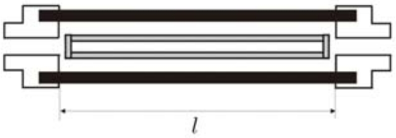
2. Wave speed in a spiral pipe and a coaxial conduit

Particular conduit structures shown in [Fig. 4] were designed and fabricated to measure wave speed in a spiral pipe(inside diameter : 4 mm, length : 0.2 m) and a coaxial conduit(inside diameter of hose : 9.8 mm, outside diameter of spiral pipe : 6.3 mm).

The conduit structure in [Fig. 4(a)] enables us to apply a spiral pipe to the wave speed measuring system shown in [Fig. 1] without any worry about oil leakage to outside. The same test system and the same test procedure as the ones in section 1 were applied to obtain the test results. Wave speed in the coaxial conduit appeared to be a little lower than that in hose.



(a) a spiral pipe



(b) a coaxial part

[Fig. 4] Test conduits to measure wave speed

Ⅴ. Pressure pulsation attenuation through resonator hose (experiment & simulation)

To confirm the validity of the suggested analyzing method of pulsating flow in hoses, the author investigated pressure attenuation characteristics for some resonator hoses by experiments and simulations. [Fig. 1] shows the structure of the resonator hoses used in the experiment.

The test hoses shown in [Fig. 1] has a spiral pipe with positive direction. The hose material is NBR/CR and the hose length is 0.3 m. Physical parameters' values related to the test resonator hose and test conditions are summarized in <Table 1>

[Fig. 5] and 6 show the experiment and simulation results for resonator hoses.

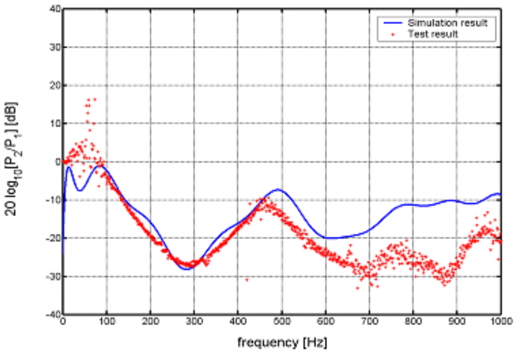
For the simulation, the measured wave speed data were utilized. In [Fig. 5, and 6], there were comparatively good agreements between the experimental results and the simulated results in the frequency range lower than 600 Hz. From these results, the validity of the analyzing method for pulsating flow in resonator hoses was confirmed.

<Table 1> Physical constants in the test system

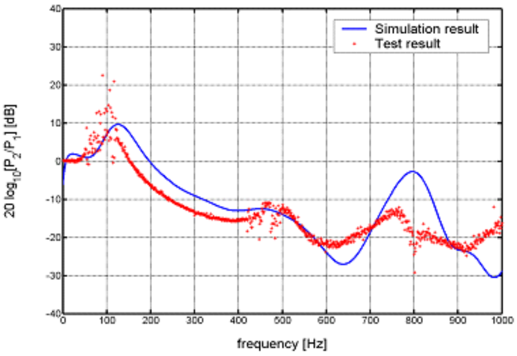
mean pressure	70 bar	inside diameter of spiral pipe	4.2 mm
mean flowrate	0 L/min	inside diameter hose	9.8 mm
length of resonator hose	0.3 m	outside diameter of spiral pipe	6.3 mm
length of spiral pipe		0.1 m, 0.25 m	

Ⅵ. Conclusions

In this study, the author suggested a new method for analyzing pulsating flow in hose based on wave speed data measured through a preliminary test. Wave speed data in each component of the object resonator hoses were measured through preliminary experiments. Finally, with several object resonator hoses, pressure attenuation characteristics were investigated by experiments and simulations. There were comparatively good agreements between the experimental results and the simulated results in the frequency range lower than 600 Hz. From these results, the validity of the analyzing method for pulsating flow in resonator hoses was confirmed.



[Fig. 5] $|P_2/P_1|$, hose: 0.3, spiral 0.25 m



[Fig. 6] $|P_2/P_1|$, hose: 0.3m, spiral pipe: 0.1m

The newly suggested method for analyzing pulsating flow in resonator hoses based on wave speed data measured in each component of a resonator hose could be used for computing the pulsation flow, evaluating the transmission loss of resonator hoses, and eventually for optimum design of resonator hoses.

Acknowledgement

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