DEVELOPMENT OF STANDARD TESTING PROCEDURE FOR EXPERIMENTALLY DETERMINING INHERENT SOURCE PULSATION POWER GENERATED BY HYDRAULIC PUMP

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Abstract

This paper reports on the experimental determination of the level of inherent pulsation power generated by a hydraulic pump, using both a test method newly developed for the measurement of fluid pulsation power in a pipeline and a theoretically derived conversion equation for eliminating the influence of a hydraulic circuit on the measurement. The suitability of the test procedure as a standard method for assessment of the inherent source pulsation power of a hydraulic pump is confirmed.

First, it was determined that the pulsation power in a pipeline can be measured using a pressure sensor unit called the "pulsation intensity probe", which utilizes the same measurement principle as a conventional "sound intensity probe", with good repeatability and with sufficient accuracy for practical usage. Next, a standard test procedure for determining the inherent source pulsation power of a hydraulic pump, which is independent of the hydraulic circuit, from the measurements of a pulsation power in a reference pipe was proposed. Finally, it was verified from the experimental measurements and simulations that this proposed standard test method is very useful for both absolute and relative assessments of the level of source pulsation power of a hydraulic pump.

Keywords: hydraulic pump, fluid-borne vibration, pressure pulsation, pulsation power, standard test method

1 Introduction

Generally, the major noise and vibration generated in hydraulic pumps can be classified into the following two types: the sound that directly radiates from the pump casing and the delivery-flow pulsations, which are the major excitation sources of fluid-borne vibration generated in a hydraulic circuit. Of these, in regard to the directly radiated sound, a method of measuring airborne noise levels has been standardized by ISO 4412: 1990, with which it is also possible to indirectly estimate a sound power level. In addition, a method standardized by ISO 16902: 2003 enables the sound power level to be directly determined using sound intensity techniques.

In regard to assessment of the pulsation source characteristics of a hydraulic pump, to date, just two quantities, namely, the delivery flow pulsation and the source impedance, have been used as the inherent characteristic values of a pump (Edge and Johnston, 1990; Weddfelt, 1992; Kojima, 1992). ISO 10767-1: 1996 has been established to standardize the test method for experimentally determining these two quantities. In addition, the acoustic blocked pressure, which is expressed as a product of the above two quantities, is also an inherent characteristic value of a pump, and a method for measuring it has been standardized by ISO 10767-3: 1997. However, the fluid pulsation power, which is given by the product of pressure pulsation and flow pulsation, and which is equivalent to the sound power for directly radiating sound, has not been used as the inherent characteristic value for a pump pulsation source. This is because pump-induced pressure pulsation, namely, the pump-induced fluid pulsation power, greatly depends on the wave propagation characteristics of the pipeline system as well as on the pump delivery flow pulsation, and hence the pulsation power measured only in a pipeline is not an inherent characteristic value of a pump. Furthermore, to the best of our knowledge, no papers dealing with fluid pulsation power in a pipeline in detail have been published to date.

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In the meantime, to design quieter hydraulic systems by controlling the fluid-borne vibration in a pipeline, it seems more reasonable to use the pulsation power, which represents the potential power of the pulsation, rather than the pressure pulsation as an evaluation index. It is a good example of showing this that the value of transmission loss (TL) has been generally used for evaluating the attenuation performance of a hydraulic silencer, which expresses the ratio of the incident fluid pulsation power to the transmitted fluid pulsation power. Hence, also for a hydraulic pump, the development of a measurement method capable of being used to fairly assess the pulsation power is important for facilitating the design of low fluid-borne vibration hydraulic systems.

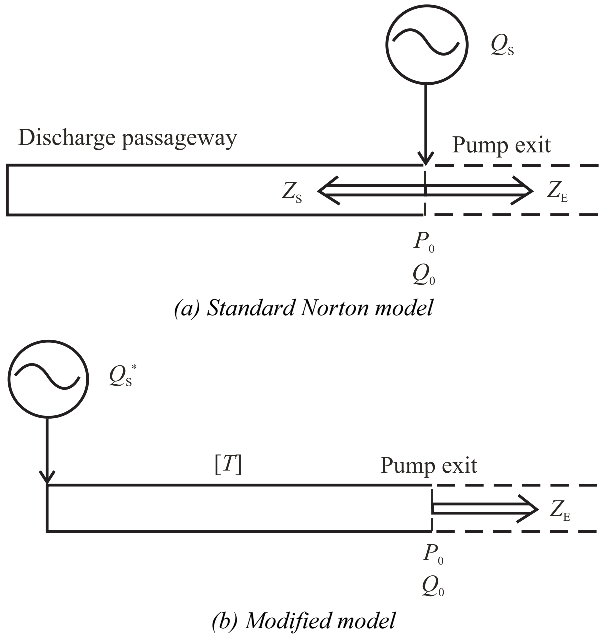


Fig. 1: *Modelling of pump pulsation source*

On the basis of the above considerations and the background information, the objective of the present work is to develop a standard test method which enables the absolute and the relative assessment of the source pulsation power of a hydraulic pump. Specifically, a standard test procedure is proposed for experimentally determining the inherent source pulsation power of a hydraulic pump, which is independent of a hydraulic circuit connected to a pump, from the measured value of pulsation power in a reference pipe; its usefulness is then examined by performing experimental measurements and simulations.

2 Modelling of Pump Pulsation Source and Experimental Measurements

2.1 Modelling of Pump Pulsation Source

The pump pulsation source of fluid-borne vibration is generally modeled as a delivery flow pulsation Q_s generating in parallel with an impedance Z_s at the exit of the pump as shown in Fig. 1(a). This model is called the standard "Norton" model, and Q_s and Z_s represent the inherent characteristic values for the pump pulsation source. However, neither Q_s nor Z_s can be measured directly. Therefore, many methods for determining these quantities indirectly from measurements of pressure pulsations in a reference pipe have been devised (Edge and Johnston, 1990; Weddfelt, 1992; Kojima, 1992).

In a real pump, however, the delivery flow pulsation generating mechanism is situated near the inner end of the discharge passageway as shown in Fig. 1(b).This model is called the "modified" model, and the flow pulsation Q_s* and the transfer matrix parameter [*T*] of the discharge passageway represent the inherent characteristic values for the pump pulsation source.

A relationship between the characteristic values in the above two models can be obtained as follows.

For the standard Norton model, the flow pulsation harmonic Q_0 and the pressure pulsation harmonic P_0 at entry (x = 0) of the connecting pipe can respectively be described by the equations,

$$Q_0 = \frac{Z_S}{Z_S + Z_E} Q_S \tag{1}$$

$$P_0 = \frac{Z_S Z_E}{Z_S + Z_E} Q_S \tag{2}$$

where Z_E is the entry impedance of the connecting pipe.

In addition, in the case of $Z_E = \infty$, the pressure pulsation harmonic P_0 at $x = 0$ becomes

$$P_0 = Q_S Z_S \equiv P_B \tag{3}$$

The acoustic blocked pressure, P_B, is also an inherent characteristic value which represents the potential for the pulsation source of a hydraulic pump, and a method of measurement for it has been standardized by 10767-3: 1997.

Next, for the modified model, if the discharge passageway can be assumed to be represented by a uniform pipe with length l_p, characteristic impedance Z_{OP} and wave propagation coefficient β, a four-terminal transfer matrix can be expressed by the following equation:

$$[T] = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \cosh(\beta l_P) & Z_{OP}\sinh(\beta l_P) \\ \frac{1}{Z_{OP}}\sinh(\beta l_P) & \cosh(\beta l_P) \end{bmatrix} \tag{4}$$

Thus, the following relational expressions can be derived from Eq. 1, 2 and 4:

$$Z_S = \frac{T_{22}}{T_{21}} = \frac{Z_{OP}}{\tanh(\beta l_P)} \tag{5}$$

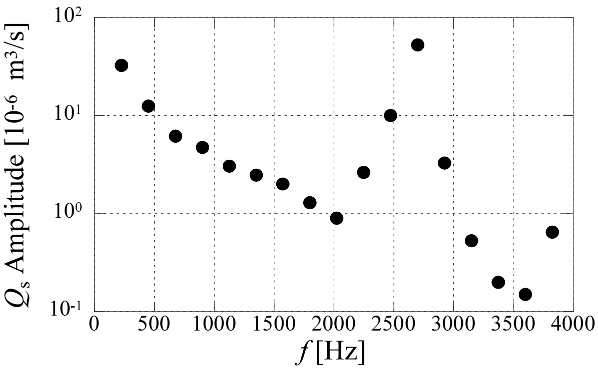
$$Q_S^* = T_{22} Q_S = \cosh(\beta l_P) Q_S \tag{6}$$

2.2 Experimental Results of Pulsation Source of Test Axial Piston Pump

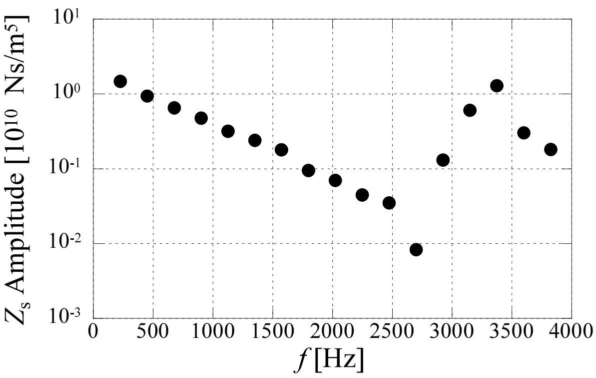
Prior to carrying out measurements of pulsation power, the delivery flow pulsation Q_s and the source impedance Z_s of the test axial piston pump (having 9 pistons) were estimated using the "two pressures/two systems" method (Kojima, 1992). Figure 2 shows an example of the measured amplitude spectra of delivery flow pulsation Q_s and the frequency characteristics of source impedance Z_s (the measured phase spectra of Q_s and Z_s are omitted on account of limited space). Resonance of a quarter wavelength mode appears clearly at a frequency of around 2700 Hz in the spectra of Q_s and Z_s. Hence, it is found that the discharge passageway in the pump casing can be approximately modeled by a uniform pipe with a length of around 0.13 m assuming the speed of sound to be 1390 m/s ($l_p = 1390 / (4 \times 2700) \approx 0.13$ m).

3 Theoretical Analysis of Pump-Induced Pulsation Power in the Reference Pipe

3.1 Hydraulic Pipeline System to be Studied



(i) Delivery flow pulsation Q_s



(ii) Source impedance Z_s

Fig. 2: *Measured amplitude spectra of delivery flow pulsation Q_s and source impedance Z_s of test axial piston pump*

A simple fluid circulating circuit shown in Fig. 3 was chosen as a hydraulic pipeline system to be studied. The test axial piston pump and the loading throttle valve are installed at the upstream end (x = 0) and the downstream end ($x = L$), respectively, of the reference pipe. The reference pipe has known wave propagation characteristics.

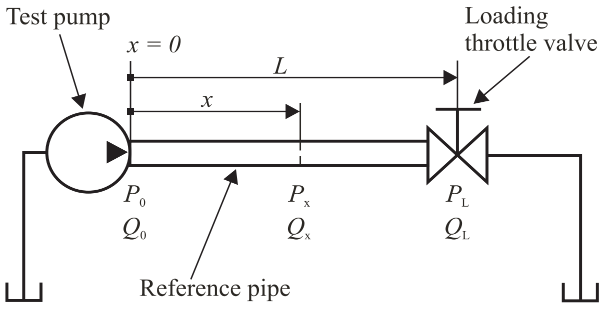


Fig. 3: *Hydraulic circuit for simulation analysis*

3.2 Pressure and Flow Pulsations in a Reference Pipe and their Progressive and Regressive Wave Components

The relationships between the harmonic components of pressure pulsations and flow pulsations at the upstream end (x = 0), the downstream end ($x = L$) and at any point x along the reference pipe, P_0, Q_0, P_L, Q_L and P_x, Q_x, can be expressed by the following equations using the four-terminal transfer matrix in the frequency domain

$$\begin{pmatrix} P_L \\ Q_L \end{pmatrix} = \begin{pmatrix} \cosh(\beta L) & -Z_0 \sinh(\beta L) \\ -\dfrac{1}{Z_0}\sinh(\beta L) & \cosh(\beta L) \end{pmatrix} \begin{pmatrix} P_0 \\ Q_0 \end{pmatrix} \tag{7}$$

$$\begin{pmatrix} P_x \\ Q_x \end{pmatrix} = \begin{pmatrix} \cosh(\beta x) & -Z_0 \sinh(\beta x) \\ -\dfrac{1}{Z_0}\sinh(\beta x) & \cosh(\beta x) \end{pmatrix} \begin{pmatrix} P_0 \\ Q_0 \end{pmatrix} \tag{8}$$

where Z_0 is the characteristic impedance and β the wave propagation coefficient of the reference pipe. Here, using the standard Norton model, the boundary condition at x = 0 is expressed by the following equation:

$$Q_S = Q_0 + \frac{P_0}{Z_S} \tag{9}$$

If we let Z_L be the impedance of the loading throttle valve, then the boundary condition at x=L is expressed by the equation

$$\frac{P_L}{Q_L} = Z_L \tag{10}$$

From Eq. 7 to 10, the following expressions can be derived for the pressure pulsation P_x and flow pulsation Q_x at any point x along the reference pipe as a functions of Q_s and Z_s

$$P_x = \frac{Z_L \cosh\{\beta(L-x)\} + Z_0 \sinh\{\beta(L-x)\}}{\left(\dfrac{Z_L}{Z_0} + \dfrac{Z_0}{Z_S}\right)\sinh(\beta L) + \left(1 + \dfrac{Z_L}{Z_S}\right)\cosh(\beta L)} Q_S \tag{11}$$

$$Q_x = \frac{\cosh\{\beta(L-x)\} + \dfrac{Z_L}{Z_0}\sinh\{\beta(L-x)\}}{\left(\dfrac{Z_L}{Z_0} + \dfrac{Z_0}{Z_S}\right)\sinh(\beta L) + \left(1 + \dfrac{Z_L}{Z_S}\right)\cosh(\beta L)} Q_S \tag{12}$$

In addition, using the modified model as a pump pulsation source and assuming that the characteristic impedance of the discharge passageway Z_{OP} is equal to that of the reference pipe Z_0, the following expressions can be derived for the pressure pulsation $P_{x'}$ and the flow pulsation $Q_{x'}$ at any point x' (= $x + l_p$) from the inner end of the discharge passageway as functions of Q_s* and L' ($= L + l_p$).

$$P_{x'} = \frac{Z_L \cosh\{\beta(L'-x')\} + Z_0 \sinh\{\beta(L'-x')\}}{\frac{Z_L}{Z_0}\sinh(\beta L') + \cosh(\beta L')} Q_S^* \quad (13)$$

$$Q_{x'} = \frac{\cosh\{\beta(L'-x')\} + \frac{Z_L}{Z_0}\sinh\{\beta(L'-x')\}}{\frac{Z_L}{Z_0}\sinh(\beta L') + \cosh(\beta L')} Q_S^* \quad (14)$$

Once the harmonic components P_x and Q_x of the pressure pulsation and the flow pulsation at position x (or x') are determined, their progressive wave and regressive wave components, P_{xp}, Q_{xp} and P_{xr}, Q_{xr}, can be obtained by the following equations

$$P_{xp} = \frac{1}{2}(P_x + Z_0 Q_x) \quad (15)$$

$$Q_{xp} = \frac{1}{2Z_0}(P_x + Z_0 Q_x) \quad (16)$$

$$P_{xr} = \frac{1}{2}(P_x - Z_0 Q_x) \quad (17)$$

$$Q_{xr} = -\frac{1}{2Z_0}(P_x - Z_0 Q_x) \quad (18)$$

3.3 Pulsation Power in Reference Pipe and its Progressive and Regressive Wave Components

Once P_x and Q_x have been determined from Eq. 11 and 12 (or Eq. 13 and 14), the active component W_a of the time-averaged (mean) pulsation power W at any point x in the reference pipe can be calculated from the following equation in the same manner as sound intensity (Fahy, 1989; Norton, 1989):

$$W_a = \frac{1}{2}\mathrm{Re}\left[P_x Q_x^*\right] = \frac{1}{2}\left\{\mathrm{Re}[P_x]\mathrm{Re}[Q_x] + \mathrm{Im}[P_x]\mathrm{Im}[Q_x]\right\} \quad (19)$$

where Re[] and Im[] denote the real and the imaginary parts of a variable, respectively, and the superscript suffix * the complex conjugate.

Likewise, the progressive wave component W_{ap} and the regressive wave component W_{ar} of W_a defined as Eq. 20 can also be calculated by Eq. 21 and Eq. 22, respectively, based on Eq. 15 to 18.

$$W_a = W_{ap} - W_{ar} \quad (20)$$

$$W_{ap} = \frac{1}{2}\left\{\mathrm{Re}[P_{xp}]\mathrm{Re}[Q_{xp}] + \mathrm{Im}[P_{xp}]\mathrm{Im}[Q_{xp}]\right\} \quad (21)$$

$$W_{ar} = \frac{1}{2}\left\{\mathrm{Re}[P_{xr}]\mathrm{Re}[Q_{xr}] + \mathrm{Im}[P_{xr}]\mathrm{Im}[Q_{xr}]\right\} \quad (22)$$

4 Measurements of Pump-Induced Pulsation Power in the Reference Pipe

4.1 Principles of the Measurement Method

If both the harmonic components of the pressure pulsation and flow pulsation in the reference pipe can be experimentally determined, measurement values of the harmonic components of the pulsation power W_a, W_{ap}, and W_{ar} can be obtained from Eq. 19, 21 and 22. Therefore, to predict the pulsation power, it is necessary to obtain the flow pulsation, which can not be measured directly, by any method. In this study, a method using a device called a "pulsation intensity probe" was adopted. The probe consists of a pair of pressure transducers as shown in Fig. 4 and utilizes the same measurement principle as a conventional sound intensity probe consisted of a pair of microphones, which is well known in the field of acoustics (Fahy, 1989). As the details of this proposed method have been described elsewhere (Kojima, 1990), only the end result is described here on account of limited space.

The time history of flow variation $q_x(t)$ at the position x can be given in the form of the following recurrence equation:

$$q(t) = e^{-R_f \Delta t} q_x(t-\Delta t) + \frac{A\Delta t}{2\rho\Delta x} e^{-R_f \Delta t/2} \left\{p_1(t-\Delta t) - p_2(t-\Delta t) + p_1(t) - p_2(t)\right\} \quad (23)$$

where A is the cross-sectional area of the reference pipe, x the distance between the two pressure transducers, t the sampling period, R_f the resistance factor of pipe flow (= 8 v / r_0^2, v: fluid kinematic viscosity, r_0: inner radius of reference pipe), and ρ the fluid density.

The time history of pressure variation $p_x(t)$ at a position x is assumed to approximately be the average value of $p_1(t)$ and $p_2(t)$ as follows:

$$p(t) = \frac{p_1(t) + p_2(t)}{2} \quad (24)$$

Next, the real and imaginary parts of the complex harmonic components of the pressure pulsation P_x and the flow pulsation Q_x are obtained by performing spectral analyses of $p_x(t)$ and $q_x(t)$, and then real and imaginary parts of the progressive and the regressive wave components of both the pressure and flow pulsations are derived from Eq. 15 to 18. Finally, the active component W_a of the time-averaged pulsation power can be obtained by substituting the real and imaginary parts of P_x and Q_x into Eq. 19, and the progressive wave component W_{ap} and the regressive wave component W_{ar} of W_a can be obtained by substituting the real and imaginary parts of of the progressive and regressive components of P_x and Q_x into Eq. 21 and 22.

In addition to the above, it has been confirmed that results obtained by treating the fluid motion between the two pressure transducers of the pulsation intensity probe as a distributed parameter system and as a lumped parameter system (as in this proposed method) are almost same in a frequency range under around 2.5 kHz (specifically, the difference between them is about 5 % at 2.0 kHz).

4.2 Experimental Apparatus

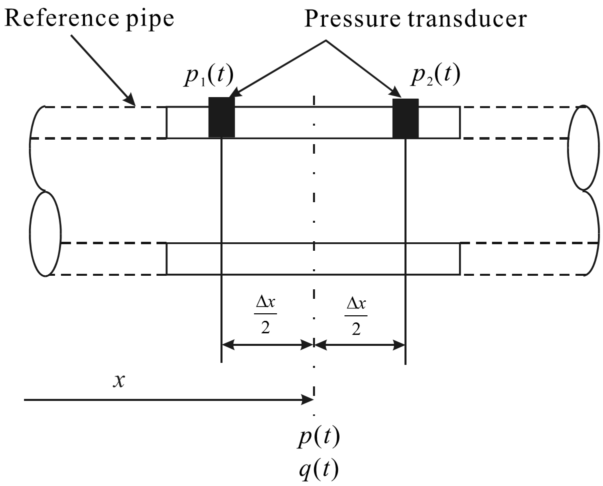


Fig. 4: *Schematic diagram of "pulsation intensity probe"*

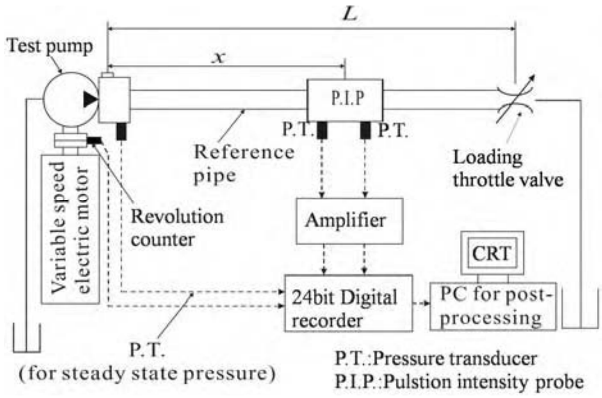


Fig. 5: *Experimental apparatus of standard test method for pump source pulsation power*

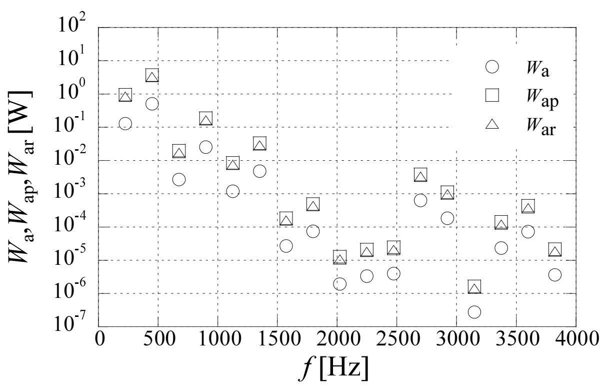


Fig. 6: *Experimental measurements of pulsation power W_a and its progressive and regressive wave components W_{ap} and W_{ar} in a reference pipe*

The arrangement of the hydraulic test circuit and the instrumentation necessary for the experimental determination of pump-induced pulsation power in a reference pipe is depicted in Fig. 5. A straight steel pipe with a 19.6 mm inner diameter for high pressure use was used as a reference pipe. The pulsation intensity probe shown in Fig. 4 was installed between the test axial piston pump at the upstream end and the loading throttle valve at the downstream end of the reference pipe. Piezoelectric pressure sensors were used as pressure transducers for the pulsation intensity probe. The distance between the two pressure transducers, x, was determined to be 60 mm, considering both the frequency range of interest (from around 200 Hz to 2.5 kHz in this study) and the resolving power of the pressure transducer. Voltage signals from the pair of pressure transducers in the pulsation intensity probe, $p_1(t)$ and $p_2(t)$, were fed into a digital recorder with a 24 bit A/D converter in periods of 0.8 s at a sampling frequency of 10.24 kHz. Spectral analyses of the pressure and flow variations, $p_x(t)$ and $q_x(t)$, were carried out by calculating discrete Fourier transforms of the time history data at intervals of 1.25 Hz on a PC as post-processing.

In this study, since all the experiments were performed under a constant pump rotational speed of 1500 rpm, the fundamental frequency of pump-induced pulsation was always 225 Hz.

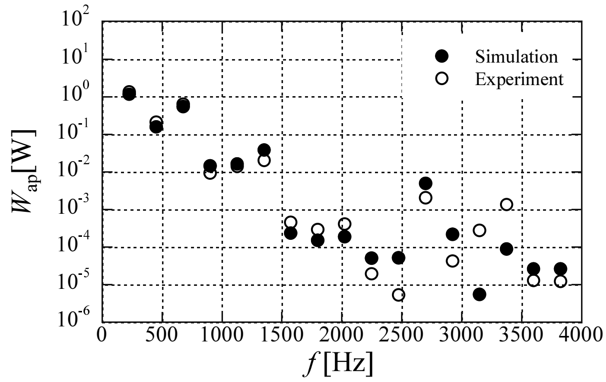
4.3 Experimental Results and Considerations

An example of the measurement results of the amplitude spectra of pulsation power W_a, and its progressive wave component W_{ap}, and regressive wave component W_{ar} in the reference pipe are shown in Fig. 6. Figure 7 shows comparisons of measurement results with simulation results for the progressive wave component W_{ap} in the reference pipe. In Fig.7, cases (i) and (ii) indicate the influence of pipe length L, and cases (a) and (b) the influence of measurement location x. Of these, case (i) of L = 0.885 m (L' = 0.885 + 0.130 = 1.015 m) and case (ii) of L = 1.391 m (L' = 1.391 + 0.130 = 1.521 m) are examples in which resonance of pump-induced pulsation is generated in an oil column in a reference pipe at harmonic frequencies of integer multiples of the 3rd order (f_3 = 675 Hz, f_6 = 1350 Hz, f_9 = 2025 Hz,.....;.) and integer multiples of the 2nd order (f_2 = 450 Hz, f_4 = 900 Hz, f_6 = 1350 Hz,.....), respectively. Further, the reflection factor of the pulsation power at the loading valve with impedance Z_L is given by the following equation (square of reflection coefficient of pressure wave):

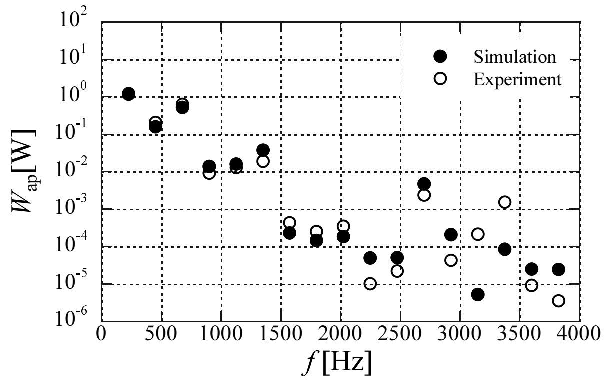
$$R = \frac{W_{ar}}{W_{ap}} = \left(\frac{Z_L - Z_0}{Z_L + Z_0} \right)^2 \tag{25}$$

For instance, in the case of the experimental conditions described in Fig. 6 and 7 (N = 1500 rpm, Q_d = 333 x 10^{-6} m^3/s and P_d = 21 MPa), the reflection factor R is around 0.85.

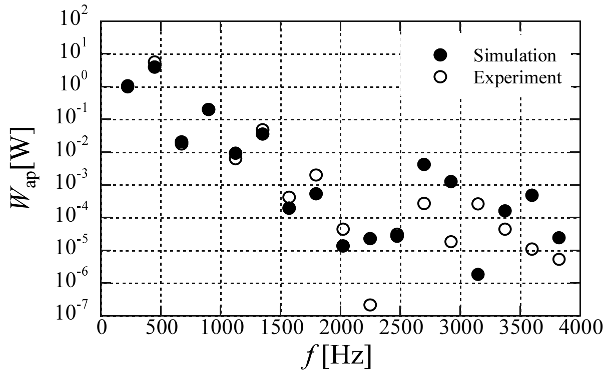
From Fig. 6 and 7 (and from other results omitted on account of limited space), the following is found: (1) the measured values of W_a, W_{ap} and W_{ar} agree well with the simulation values calculated from Eq. 19 to 22 using the values of Q_s and Z_s measured separately, as described in Section 2; that is, the pulsation power in a pipeline can be measured accurately by using the proposed pulsation intensity technique; (2) the values of W_a, W_{ap} and W_{ar} greatly depend on the length of pipeline (i.e., pipeline system), but negligibly depend on the measurement position along the reference pipe (with the proviso that values downstream of wave propagation are a little smaller than those upstream due to viscous friction); (3) the harmonic amplitudes of these quantities significantly increase at harmonic frequencies coinciding with the resonance frequencies of the oil column in the reference pipe; and(4) the ratio of measured values of W_{ap} and W_{ar} almost exactly agrees with the theoretical reflection factor of the loading valve calculated from Eq. 25.



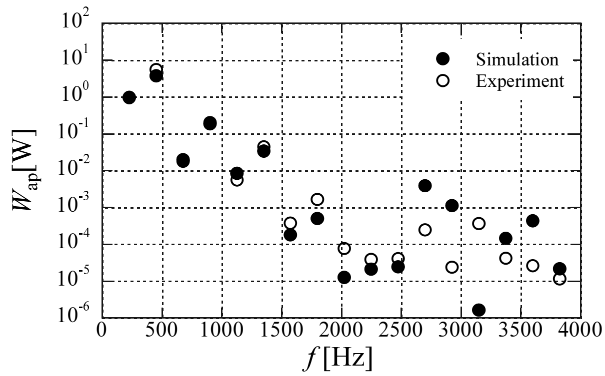
(a) x = 0.215 [m], L = 0.885 [m]



(b) x = 0.639 [m], L = 0.885 [m]



(a) x = 0.215 [m], L = 1.391 [m]



(b) x = 0.639 [m], L = 1.391 [m]

Fig. 7: *Comparisons of experimental measurements with simulations for progressive wave component W_{ap} of pulsation power in a reference pipe (P_d = 21 MPa)*

In addition, the following can be considered. In the case of R = 1 and R_f = 0, $W_{ap} = W_{ar}$, and hence W_a = 0. It is only natural from the conservation of energy that the pulsation power generated by a hydraulic pump becomes zero, though, in actuality, pressure pulsation and flow pulsation) occurs in the reference pipe. On the other hand, in the case of R = 0 (i.e., anechoic termination condition), W_{ar} = 0 and hence $W_a = W_{ap}$; that is, the pulsation power generated by a hydraulic pump W_a becomes maximum. Therefore, it seems reasonable that the progressive wave component W_{ap} of the active component of the time-average pulsation power W_a should be used for assessment of the inherent source pulsation power of a hydraulic pump. Hence, consideration of the progressive wave component of pump-induced pulsation power is hereafter emphasized.

5 Proposal of a Standard Test Procedure for Experimentally Determining the Inherent Source Pulsation Power of a Hydraulic Pump

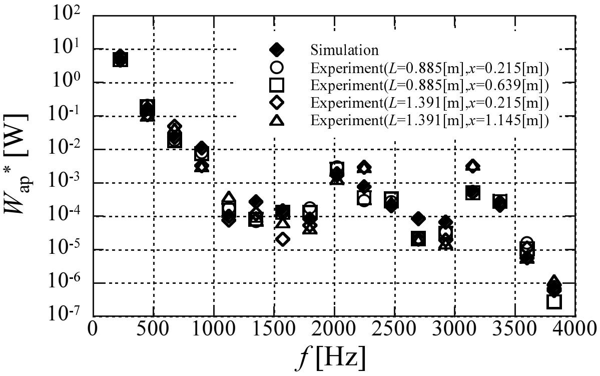
The expression for the progressive wave component W_{ap}* of the active component W_a* of the time-averaged (mean) pulsation power generated in the hydraulic system, in which the loading valve is directly connected to the pump exit, can be derived as follows. The flow pulsation Q_0 and pressure pulsation P_0 can be obtained from Eq. 1 and 2 by letting $Z_E = Z_L$, and then the progressive wave components of P_0 and Q_0 from Eq. 15 and Eq. 16. Finally the progressive wave component W_{ap}* can be obtained using Eq. 21 as the following equation:

$$W_{ap}^{*} = \frac{1}{2Z_0}\left|G_1\right|^2\left|Q_S\right|^2 \tag{26}$$

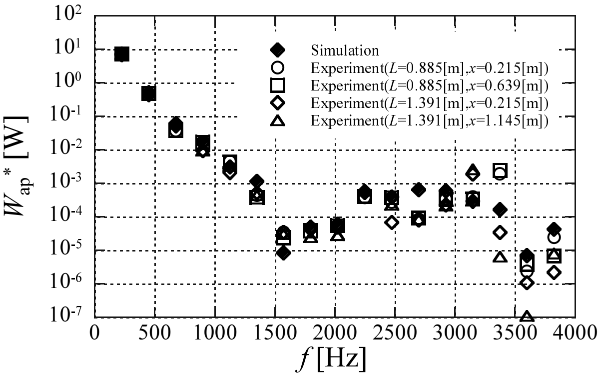
where

$$G_1 = \frac{1}{2}\frac{Z_S}{Z_S + Z_L}\left(Z_L + Z_0\right) \tag{27}$$

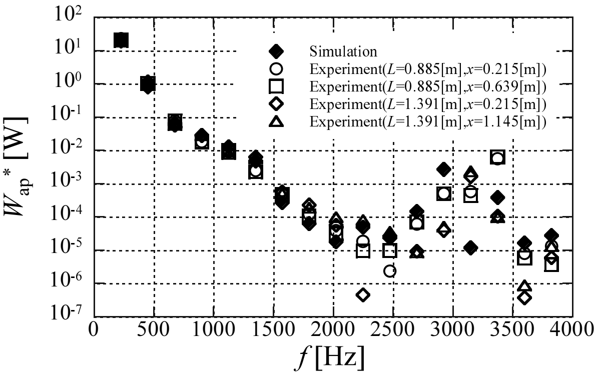
As can be seen from the above equation, W_{ap}* is an inherent characteristic value of the pump independent of the hydraulic circuit. However, it is impossible in the construction of a circuit to measure W_{ap}* by using the proposed pulsation intensity method. Therefore, in this study, a method of estimating the value of W_{ap}* from the progressive wave component W_{ap} of the active component W_a of the time-average pulsation power measured in the reference pipe connected to the pump exit was newly devised.



(i) P_d = 7 MPa



(ii) P_d = 14 MPa



(iii) P_d = 21 MPa

Fig. 8: *Comparisons of experimental measurements with simulations for progressive component W_{ap}^* of pump inherent pulsation*

As explained in Section 4.3, the value of W_{ap} negligibly depends on the position of measurement. Hence, it can be considered that the value of W_{ap} measured halfway through the reference pipe is approximately equal to that at $x = 0$ expressed by the following equation:

$$W_{\text{ap}} = \frac{1}{2Z_0}\left|G_2\right|^2\left|Q_{\text{S}}\right|^2 \tag{28}$$

where

$$G_2 = \frac{1}{2}\frac{Z_{\text{S}}}{Z_{\text{S}}+Z_{\text{E}}}\left(Z_{\text{E}}+Z_0\right) \tag{29}$$

and Z_{E} is the entry impedance of the reference pipe expressed by the following equation:

$$Z_{\text{E}} = \frac{Z_{\text{L}}\cosh(\beta L)+Z_0\sinh(\beta L)}{\frac{Z_{\text{L}}}{Z_0}\sinh(\beta L)+\cosh(\beta L)} \tag{30}$$

As can be seen from Eq. 26 and 28, the following relationship exists

$$W_{\text{ap}}^* = K\times W_{\text{ap}} \tag{31}$$

where K is a frequency-dependent coefficient (hereafter, the "conversion factor") given by the following equation:

$$K = \left|\frac{G_1}{G_2}\right|^2 \tag{32}$$

Since an unknown characteristic value of the pump Z_{s} is included in the equation of the conversion factor (Note: another characteristic value Q_{s} is not included), W_{ap}* can not be strictly estimated from W_{ap} by using Eq. 31. However, it may be said that W_{ap}* can be estimated from Eq. 31 with sufficient accuracy for practical usage, because the influence of Z_{s} on the conversion factor K is subsidiary and in addition a general value of Z_{s} can be found by the following method. That is, the length of an equivalent single pipe of discharge passageway l_{p} may be found by measuring the volume of working fluid in the passageway and dividing this by the cross-sectional area of a reference pipe, and then the general value of pump source impedance Z_{s} can be estimated.

Once each harmonic component of the progressive component of inherent pump pulsation power W_{ap}* has been determined, the overall value $\overline{W}_{\text{ap}}^*$ can be calculated from the following equation:

$$\overline{W}_{\text{ap}}^* = \sqrt{\sum_{i=1}^{I}\left\{W_{\text{ap}}^*\left(f_{\text{i}}\right)\right\}^2} \tag{33}$$

Figure 8 shows the estimated experimental values of the harmonic amplitude of W_{ap}* for P_{d} = 7 MPa, 14 MPa and 21 MPa and their simulation values calculated from Eq. 26 using the values of Q_{s} and Z_{s} measured separately.

Table 1 shows the measurement and simulation results of the overall progressive component of inherent pump pulsation power.

As can be seen from the results shown in Fig. 8 and Table 1 that, although the experimental values of harmonic amplitude of W_{ap} are greatly dependent on the length of pipeline L, that is, the hydraulic circuit, the estimated experimental values of the harmonic amplitude of W_{ap}* calculated from Eq. 31 converge to the almost same values independent of pipeline length L and measurement location of W_{ap}. Furthermore, it is also found that the estimated experimental values of harmonic amplitude of W_{ap}* agree well with those of simulations calculated using Eq. 26 except for the high-frequency range (above around 2500 Hz in this study) where the N/S ratio is large, and that the overall value $\overline{W}_{\text{ap}}^*$ can be estimated with an uncertainty of around 5 %.

In conclusion, it was verified from the above considerations that the estimated experimental values of the harmonic amplitude of W_{ap}* and the overall value $\overline{W}_{ap}^{*}$ determined using this proposed standard testing procedure can be successfully used as an index for absolute and relative assessments of the source pulsation power of a hydraulic pump.

Finally, the steps of the analysis procedure of this proposed standard test method for experimentally determining the inherent source pulsation power of a hydraulic pump called the pulsation intensity technique are shown summarily in steps 1 to 3.

Step 1: Measurement of the progressive wave component W_{ap} (measurement of its harmonic amplitude $W_{ap}(f_i)$) of the active component W_a of the time-averaged pulsation power in the reference pipe connected to the hydraulic pump being tested, using this proposed pulsation intensity probe.

Step 2: Calculation of the estimated experimental value of progressive wave component W_{ap}* (measurement of its harmonic amplitude $W_{ap}*(f_i)$) of the active component of the time-averaged inherent source pulsation power of the hydraulic pump, on the basis of the above W_{ap} and the theoretically derived pump source impedance Z_s.

Step 3: Calculation of the overall value of the inherent source pulsation power of the hydraulic pump on the basis of the above W_{ap} ($W_{ap}*(f_i)$).

Conclusions

The main conclusions derived from this study are as follows:

Table 1: Measured and simulated overall values of progressive component of inherent pump pulsation power [W]

Power \ Pressure	7MPa	14MPa	21MPa
Measured*	5.60	7.28	20.98
Simulated	5.73	6.97	19.46

* Average value of measurements shown in Fig. 8

- A method called the "pulsation intensity technique" for accurately measuring the pump-induced pulsation power and its progressive and regressive wave components generated in a hydraulic pipeline was able to be developed.
- A standard test procedure for assessment of the inherent source pulsation power level of a hydraulic pump, which is independent of a hydraulic circuit connected to the pump, was proposed, and its industrial usefulness was able to be verified by experimental measurements and simulations.

Nomenclature

f	Pulsation frequency	[Hz]
f_i	ith harmonic frequency of pump induced pulsation	[Hz]
G_1	Transfer function defined by Eq. 27	[Ns/m^5]
G_2	Transfer function defined by Eq. 29	[Ns/m^5]
K	Conversion factor defined by Eq. 32	[-]
$p(t)$	Pressure variation in time domain	[Pa]
$p_1(t)$	Pressure variation at upstream of "pulsation intensity probe"	[Pa]
p_2(t)	Pressure variation at downstream of "pulsation intensity probe"	[Pa]
P_x	Pressure pulsation harmonic at position x in reference pipe in frequency domain	[Pa]
P_{xp}	Progressive component of P_x	[Pa]
P_{xr}	Regressive component of P_x	[Pa]
q(t)	Flow-rate variation in time domain	[m^3/s]
Q_s	Pump source flow pulsation harmonic in the standard Norton model	[m^3/s]
Q_x	Flow pulsation harmonic at position x in reference pipe in frequency domain	[m^3/s]
Q_{xp}	Progressive component of Q_x	[m^3/s]
Q_{xr}	Regressive component of Q_x	[m^3/s]
r_0	Inner radius of reference pipe	[m]
t	time	[s]
W(x,t)	Instantaneous pulsation power in reference pipe	[W]
W(W(x))	Time-averaged complex pulsation power harmonic of W(x,t)	[W]
W_a	Active component (real part) of W	[W]
W_{ap}	Progressive component of W_a	[W]
W_{ar}	Regressive component of W_a	[W]
W^*	Time-averaged complex inherent pulsation power harmonic of pump	[W]
W_a^*	Active component (real part) of W^*	[W]
W_{ap}^*	Progressive component of W_a^*	[W]
$\overline{W}_{ap}^*$	Overall value of W_{ap}^*	[W]
Z_E	Entry impedance of reference pipe	[Ns/m^5]
Z_L	Impedance of loading throttle valve	[Ns/m^5]
Z_0	Characteristic impedance of reference pipe	[Ns/m^5]
Z_s	Pump source impedance	[Ns/m^5]
$ß$	Wave propagation coefficient of reference pipe	[rad/m]
ρ	Density of fluid	[kg/m^3]
ν	Kinematic viscosity of fluid	[m^2/s]

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