

Method for Objectively Evaluating Power Steering Pump Noise and its Correlation with Subjective Vehicle Feeling Judgment

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ABSTRACT

It is challenging to evaluate the source noise characteristics of a power steering pump unit by the current one-pressure method. In this research, an effective evaluation system and a single indicator are developed, based on fluid dynamics in a pipe and 3-point pressure pulsation measurement. The value of the evaluation indicator, which is obtained from pump's source flow ripples measured by the new evaluation system, is well correlated with the noise performance of power steering system in an actual vehicle. It is shown that the new evaluation system and indicator are valuable tools for investigating the pulsation characteristics of pump units, objective scaling of the source noise properties of steering systems and developing quiet power steering pumps and systems.

1. Introduction

Power steering noise is one of the issues that affect vehicle overall NVH (noise, vibration and harshness) quality. Fluidborne noise (FBN) is one type of noise that can be noticed in an automotive hydraulic power steering system. In the system, the power steering pump is the fluidborne noise source that generates fluctuating flow, i.e., flow ripples, to the system. The flow ripples of the pump interact with the connected hose, pipes and steering gearbox unit to generate pressure pulsations. The pressure pulsations are transmitted through the fluid to everywhere in the system and may excite annoying mechanical vibrations and high levels of airborne noise. In order to reduce the level of fluidborne noise and develop quiet power steering systems, it is important to effectively evaluate and monitor the noise source characteristics.

Currently, the conventional method to judge the source fluidborne noise characteristics of power steering pumps is to measure actual pressure pulsation levels at one location in a given pump-hose-valve bench system, which is named as the "One Pressure" method, as illustrated in Fig. 1. In this method, the pump is connected to the power steering hose assembly and then connected to a simple loading valve. The fluidborne noise level of the pump is evaluated by examining the pressure pulsation levels at either the hose outlet or the hose inlet. There are

several technical disadvantages with the current method that may affect the effectiveness of the evaluation. Firstly, the results obtained from this method are dependent on the entire measurement system. That is, slight changes to the dimensions of connection pipes and/or the characteristics of the loading valve will yield different results. This makes it difficult to compare test results obtained in different geographical places. Figure 2 shows an example of the pulsation results for an identical pump obtained by using the "One Pressure" method separately from the measurement systems at two different places. This example shows that the difference between the results from the two systems can be as big as 20 dB. Secondly, the results obtained may not reflect actual noise levels or trends when the pump is installed in an actual power steering system because the impedance characteristics of the bench loading valve are different from those of a

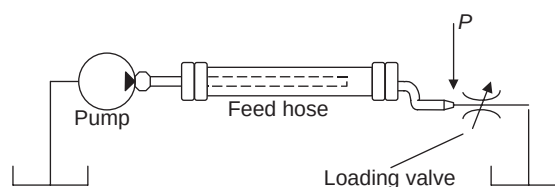


Fig. 1 Basic system of "One Pressure" method

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power steering gearbox, as shown in Fig. 3. Finally, measurement results are the combined effect of the entire measurement system and cannot be used as objective scaling for the inherent fluidborne noise properties of the pump. Therefore, it is necessary to establish a new method to evaluate the independent source characteristics of the pump unit.

The source fluidborne noise characteristics of a power steering pump which represents the pump's potential to excite FBN can be fully described by the following two parameters: source flow ripple (Q_s) and internal impedance (Z_s). Some existing efforts have been given to the development of experimental methods for evaluating the values of source flow ripple and internal impedance. Due to the system dependence of pressure pulsations, in most of the proposed methods, the characteristics of every component of the measurement circuit should be measured or established analytically first⁽¹⁾⁻⁽⁵⁾, or another (secondary) pulsation source is needed⁽⁶⁾⁻⁽⁸⁾. This makes the test circuit and measurement procedure complicated. One of the simplest and most accurate methods is the “2 Pressures/2 Systems” method proposed by Kojima⁽⁹⁾ and used by Kojima and one of the authors for hydraulic piston pumps⁽¹⁰⁾. This method can evaluate the source flow ripple and internal impedance of the pump by measuring only

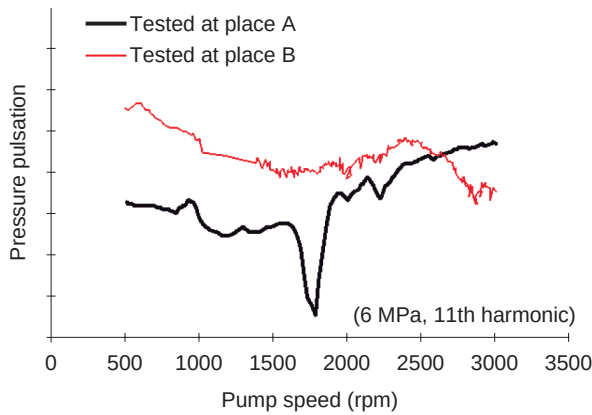


Fig. 2 Pulsations of pump measured at different places by using “One Pressure” method

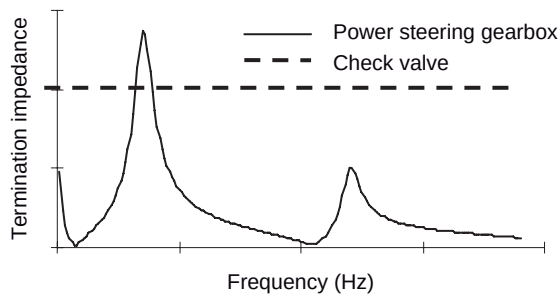


Fig. 3 Impedance characteristics of power steering gearbox and check valve

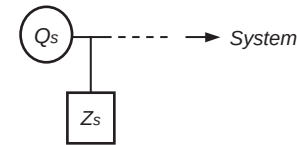
the wave propagation characteristics of pressure ripple generated by the test pump itself in a specific reference pipe. Based on this method, the “3 Pressures/2 Systems” method was proposed by one of the authors⁽¹¹⁾. This new method integrates exclusively an on-line measurement technique for the speed of sound in the fluid and a technique for eliminating flow disturbance effect on pressure sensors into the basic principle used in the existing “2 Pressures/2 Systems” method. The new method has an inherent potential to yield results with higher accuracy and higher confidence.

The work to be presented in this paper is directed toward an evaluation system and evaluation indicator for the source fluidborne noise characteristics of a power steering pump, by applying the theory of the “3 pressures/2 systems” method. After the validation on the system accuracy and repeatability, a single indicator for the source pulsation level is defined as the total pulsation energy of a pump. Then, the correlation between pump data and vehicle noise performance is presented.

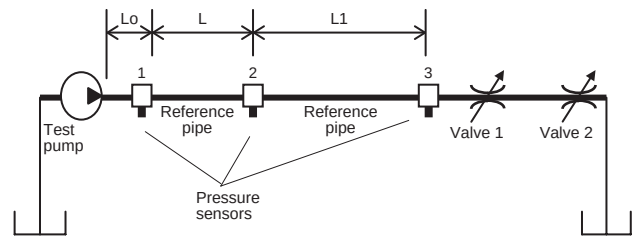
2. Theoretical approach and test system

2.1. Theoretical approach

By the standard “Norton” representation, the source fluidborne noise characteristics of the pump can be modeled as a source flow ripple, Q_s , connected in parallel with a internal impedance, Z_s , as shown in Fig. 4(a). Consider a test hydraulic circuit consisting of a test pump, a rigid pipe (hereafter referred to as the reference pipe), a connection pipe and then two loading valves separated by proper distance, as shown in Fig. 4(b). Alternative use of Valve 1 and Valve 2 allows a change to the standing wave in the circuit. On the reference pipe, there are three dynamic pressure sensors separated from the pump exit and from each other by distances of L_0 , L and L_1



(a) Pump model



(b) Measurement hydraulic circuit

Fig. 4 Pump model and basic hydraulic circuit of “3 Pressures/2 Systems” method

respectively. The circuit is called as System 1 and System 2 separately when Valve 1 and Valve 2 is used to load the system.

Consider unstable, two-dimensional, laminar viscous flow in the circuit. Based on fluid dynamics in the pipes, the source flow ripple and source impedance of the pump can be related to the pressure pulsations P_1 and P_2 from Sensors 1 and 2, as expressed by Eqs. (1) and (2), where the prime signs indicate the signals taken from System 2 with respect to the same pump rotational reference position as used in System 1. This constitutes the basic theory of the “3 Pressures/2 Systems” method⁽¹¹⁾.

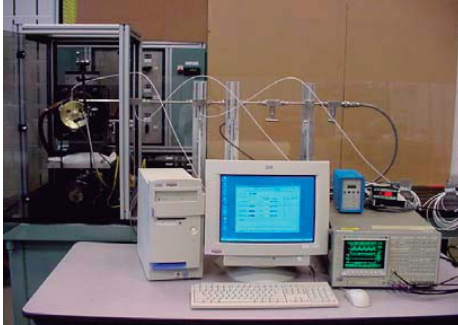
$$Q_s = \frac{j}{Z_c} \frac{P_1 P_2' - P_1' P_2}{(P_1 - P_1') \sin[\beta(L + L_0)] - (P_2 - P_2') \sin(\beta L_0)} \quad (1)$$

$$Z_s = -jZ_c \frac{(P_1 - P_1') \sin[\beta(L + L_0)] - (P_2 - P_2') \sin(\beta L_0)}{(P_1 - P_1') \cos[\beta(L + L_0)] - (P_2 - P_2') \cos(\beta L_0)} \quad (2)$$

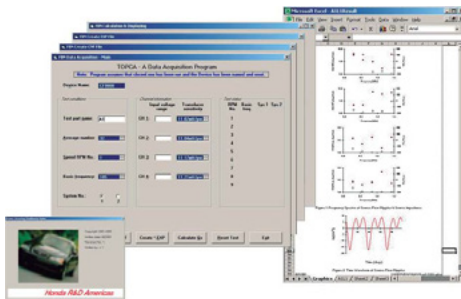
$$\text{where, } \beta = -j \frac{s \xi(\omega)}{c}$$

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

$$\xi(\omega) = 1 + \sqrt{\frac{\nu}{2r^2\omega}} - j \left[\sqrt{\frac{\nu}{2r^2\omega}} + \frac{\nu}{r^2\omega} \right]$$



(a) System hardware



(b) System software

Fig. 5 New evaluation system

In Eqs. (1) and (2), $j = \sqrt{-1}$, s is the Laplace operator, ω angular frequency ($\omega = 2\pi f$, f is frequency), ρ the fluid density, ν the kinematic viscosity of the fluid, r the inside radius of the reference pipe, c the speed of sound in the fluid. The value of c can be on-line derived from pressure signals at sensors 1, 2 and 3, based on Eq. (3) by means of the “Three Transducer” method⁽¹²⁾⁻⁽¹⁴⁾.

$$\frac{P_1}{P_2} \sin \left[\frac{\xi(\omega)\omega}{c} L_1 \right] + \frac{P_3}{P_2} \sin \left[\frac{\xi(\omega)\omega}{c} L \right] - \sin \left[\frac{\xi(\omega)\omega}{c} (L + L_1) \right] = 0 \quad (3)$$

2.2. Experimental system

Figure 5 (a) shows the hydraulic test circuit and data acquisition system for measuring the source flow ripple and internal impedance of fluid power pumps by using the theoretical approach described above.

The lengths of the reference pipe between sensors 1 and 2, the extension pipe between valves 1 and 2, and the reference pipe between sensors 2 and 3 are appropriately selected for the frequency range of interest, 0 – 1000 Hz. The data acquisition system consists of a personal computer and a four-channel Fast Fourier Transform (FFT) analyzer. The sampling of the pressure ripple signals in the FFT analyzer is triggered externally by a photoelectric sensor detecting a fixed position of the pump driveshaft. The computer is used to control the FFT analyzer for data acquisition and to perform data processing, with a general-purpose software package shown in Fig. 5(b) developed with MS Visual Basic for the interface, Fortran for the data analysis and MS Excel Macro for report generation.

3. Validation of evaluation system

3.1. Measurement accuracy

The measurement accuracy is validated by two ways. In the first way, the evaluation system is verified by comparing the predicted results of pressure ripples, based on the determined source flow ripple and internal impedance, with the measured results of pressure ripples in a pump-pipe-valve circuit. The source flow ripple and internal impedance, Q_s and Z_s , of a power steering pump is measured by the evaluation system described in the preceding section. The termination impedance, Z_t , of the valve is measured by means of two pressure signals. Then, the pressure ripple at any locations of the confirmation system can be predicted, based on the measured data of Q_s , Z_s and Z_t as well as theoretical models of fluid dynamics in pipes. Figure 6 presents an example of the comparison of the predicted and measured pressure pulsations at one location on the pipe. Similar comparison results are obtained for other points along the pipe. It is shown that there is a very good agreement between the predicted and measured results in a wide order range of the pump's flow ripple. This

indirectly verifies that the evaluation system can yield evaluation results with good accuracy.

In the second way, the length of the connection pipes of the test system is changed on purpose so that the independence of measurement results on pipe dimensions can be verified. Two different lengths, 320mm and 750mm, are randomly selected for the connection pipe between sensor 3 and valve 1. Figure 7 shows the measured source flow ripples obtained by using the connection pipes with different lengths. The figure indicates that the change to connection pipe length has little influence on the measurement results. Variations at high orders likely result from unstable motor speed and unstable internal operation conditions of the pump.

3.2. Repeatability of evaluation system

It is very important to make sure that the evaluation system can provide repeatable results before the system is used for actual application. To minimize the influence of possible internal operating uncertainty of pump, a constant displacement power steering pump is used to perform repeatability test. The pump is tested nine times on the evaluation system. To maintain similar operation conditions to the pump during each test, the driving motor is stopped and turned on again before starting each test, and all other test conditions are kept the same. Figure 8

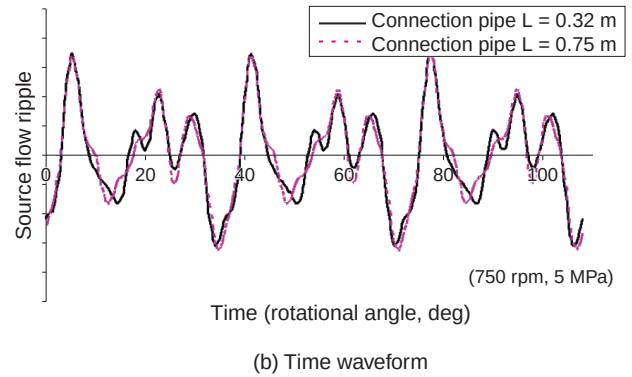
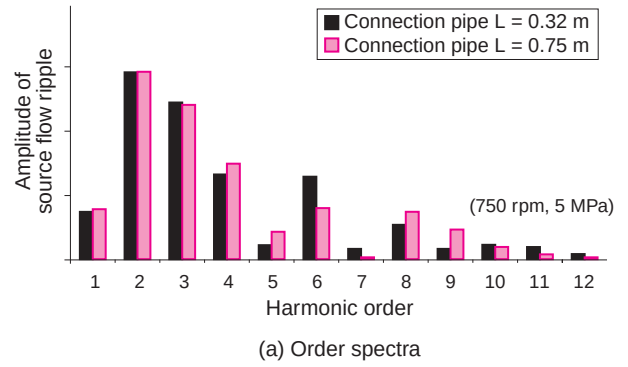


Fig. 7 Measured results of source flow ripple of pump with respect to different connection pipe lengths

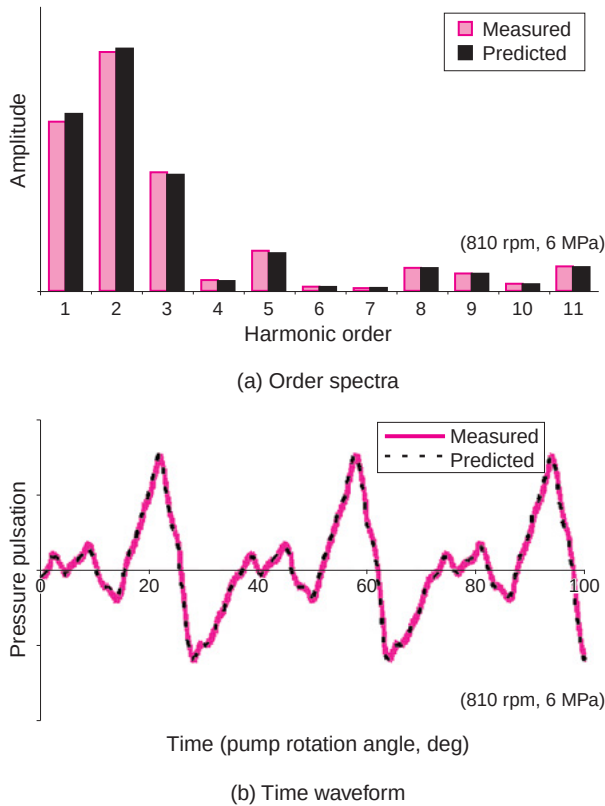


Fig. 6 Predicted and measured pressure pulsations at one location on feed pipe of pump-pipe-valve system

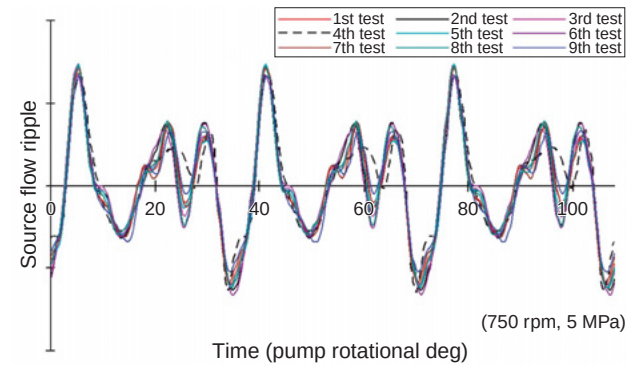


Fig. 8 Measured levels of source flow ripple of same pump from nine different tests

illustrates the time waveforms of the evaluation results for the nine tests. The results show that the evaluation system and the test pump have acceptable repeatability for practical use.

4. New evaluation indicator

Now that we can measure the source flow ripple and internal impedance of a power steering pump by using the

evaluation system based on Eqs. (1) and (2), the effect of each harmonic component on the source characteristics of the pump can be readily examined and evaluated directly from the harmonic spectra and resultant time waveform of source flow ripple. Beyond the harmonic analysis, it is also important to be able to judge the pump overall pulsation level by using a single indicator.

The source fluidborne noise characteristics are fully represented by the two parameters, that is, source flow ripple and internal impedance. The value of internal impedance is normally determined by the fluid compressibility and fluid wave propagation inside the pump discharge passageway. For a given design of pump, the layout and size of discharge passageway is fixed, and hence the internal impedance is theoretically fixed if same test fluid and temperature condition are maintained. This implies that source flow ripple is the key parameter to be considered while evaluating the source pulsation level for a certain type of pump.

A single evaluation indicator is defined here for evaluating the overall level of source pulsation level of a pump, by Eq. (4).

$$L_k = 20 \log_{10} \sqrt{\sum_{i=1}^k Q_i^2 / Q_{ref}^2} \quad (\text{dB}) \quad (4)$$

where Q_i is the i -th harmonic order of measured source flow ripple and Q_{ref} a reference value of $10^{-6} \text{ m}^3/\text{s}$.

The evaluation indicator represents physically the total power of the harmonic spectral components of source flow ripple up to the upper order of the harmonic range of interest. Since the source flow ripple is directly related to the pressure pulsations in power steering systems and the pressure pulsations are related to the system vibrations and noise, L_k is an indicator reflecting the potential of a pump to cause pulsation-induced noise in a power steering system.

In addition, an A-weighting filter can be easily included in Eq. (4), if necessary.

5. Correlation between pump data and vehicle performance

According to source-path-receiver noise transferring manner, in an actual vehicle, if the power steering hose and gearbox are fixed and the vehicle sound treatment package is kept the same, the power steering noise heard in cabin should be correlated to the source, that is, the pump's characteristics.

A correlation test between pump data and vehicle performance is performed on a vehicle. Four pumps with basically same design but different levels of source flow ripple are specially made for this test. Those pumps are firstly evaluated in terms of the total power of source flow

Table 1 10-point rating scale for subjective judgment

Rating	Judgment
10	Excellent
9	Very good
8	Good
7	Acceptable
6	Marginally acceptable
5	Borderline unacceptable
4	Unacceptable
3	Poor
2	Very poor
1	Extremely poor

ripple by using the evaluation system under the following two sets of test conditions: (1) fluid pressure of 1 MPa and pump speed of 750 rpm; (2) fluid pressure of 5 MPa and pump speed of 750 rpm and 1100 rpm.

As the evaluation of vehicle performance, in-car power steering noise is subjectively judged separately for the four different pumps by several technical experts under the following two different conditions corresponding to those used in bench test: (1) no or small steering input and idle engine speed; (2) steering input of partial loading and full lock, and engine speeds of idle and 1200 rpm. The subjective judgments are made based on a 10-point ranking system, as shown in Table 1.

Figure 9 shows the test results for the correlation of the test pumps and the vehicle noise performance with pump's total power of source flow ripple in x-axis and subjective judgment of vehicle noise in y-axis. It is shown that there is a very good correlation between the pump data and vehicle performance. This indicates that the fluidborne noise characteristics of power steering pump can be evaluated by the total power of source flow ripple.

From the correlation data, the fluidborne noise

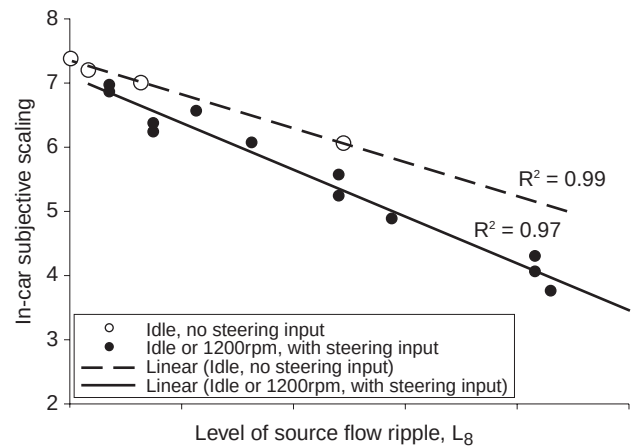


Fig. 9 Correlation of pump unit data and vehicle noise performance

(pressure pulsation) specifications of pump can be specified easily based on the flow ripple level at the cross points of correlation lines and the minimum requirement line of vehicle performance.

6. Application examples

As one application example, the new evaluation system and indicator are used to benchmark Civic-class competitor's pumps. Six pumps on different small-size cars in the North American market are selected for the benchmarking test. (For confidentiality purpose, the manufacturers information are not disclosed here.)

The pumps are tested under two different conditions which duplicate the operation status of interest for power steering noise concerns. Condition 1 is set to replicate the idle engine speed without or with very little steering input, while Condition 2 is set to replicate idle engine speed with continuous steering turning input.

Figure 10(a) shows the source fluidborne noise levels with a cutoff order of 6 under Condition 1, and Fig. 10(b) shows the results under Condition 2. It is revealed that those pumps have quite different source characteristics, and some are good for no or small steering input while

the others are good for continuous steering input. Among them, Pump 5 has the best balance for both conditions.

7. Conclusions

A new system for evaluating fluidborne noise characteristics of automotive power steering pump units has been developed, by using the "3 Pressures/ 2 Systems" method. A single evaluation indicator in terms of the total power of pump's flow ripple harmonic components was proposed for the level of source fluidborne noise of power steering pumps. The value of the indicator can be easily calculated from the harmonic spectral results obtained by the evaluation system. For the first time, the fluidborne noise level of pumps was correlated with the noise performance of power steering systems in an actual vehicle, and a high degree of correlation achieved. From the correlation data, the pulsation specifications of a pump unit can be easily and logically established.

It has been shown that the evaluation system is effective for obtaining objective data and the new, single indicator is valuable for providing objective scaling for the inherent noise characteristics of a power steering pump unit. They can be useful tools for developing quiet power steering pumps and hence quiet power steering systems.

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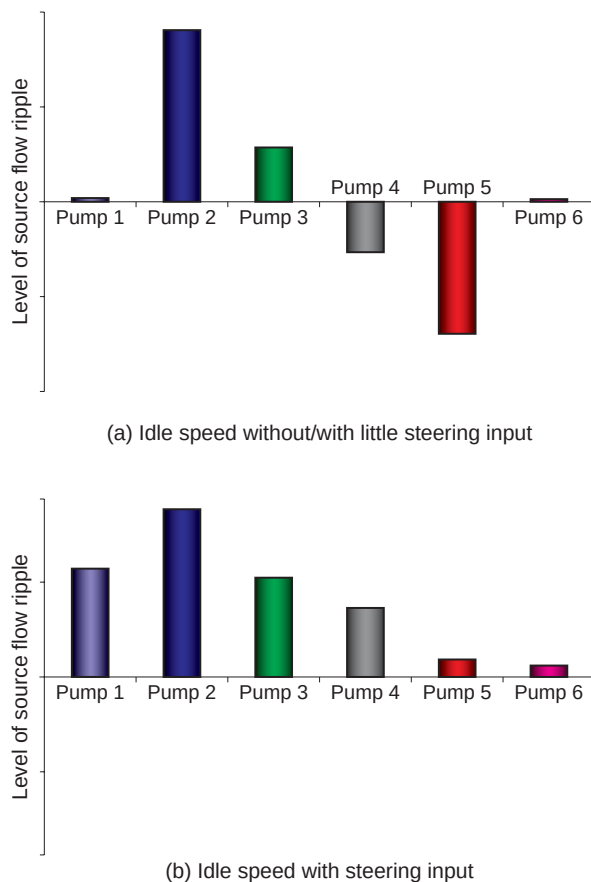


Fig. 10 Benchmarking results of Civic-class competitor's pumps

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