Study on Noise Reduction of High-Powered Suction Truck (Consideration of phase difference between two pressure fluctuations of SHAC silencers）

Kunihiko Ishihara, Tomoya Hamada, Toshinobu Iwamoto

Abstract— **A main noise source of the high powered suction truck is a pressure fluctuation of a blower and the noise is radiated from the final component named "4th catcher". Two holes are provided at the upper and the lower parts of the blower as a means to get cool the blower and two SHACs (Self Help Air Conditioner) are connected to the blower by two hoses. The present study aims to clarify the achievement of the noise reduction to use the phase difference which can be made by two different lengths of hoses. As a result, the use of fluctuating pressure data before connection of two ports doesn't go well in the prediction of the noise reduction but go well by use of the data after the connection and the phase difference is the most important factor in the prediction of the noise reduction in using the idea of the interference type silencer.**

Index Terms— **Noise Control, Interference Type Silencer, High-Powered Suction Truck, Resonance.**

I. INTRODUCTION

A high powered-suction truck used cleaning of side ditch has been operated at night in order to avoid traffic confusion in major city [1]. It is necessary to reduce the noise to be required silence at night. However a root blower used here makes a strong pulse in a piping and it is said that the root blower is not suitable for the noise reduction. The silencer has usually been set the downstream of the blower. Because it has been considered that the noise source of the suction truck exists at a final exit of the piping. Many studies on the noise reduction for the high powered suction truck have been performed by many authors [2]～[8]. By the way, the high powered suction truck adopts SHAC (Self Help Air Conditioner）as a cooling method. In a wet type suction truck（$4m^3$ class）, a blower has two ports of the SHAC and sucks down an air from the SHAC silencers by hoses.

Previously, it has suggested that the sound waves with the phase difference groups together the surge tank, reduces the noise. Then in this paper, it will be discussed whether this idea could suppress the noise or not.

II. EXPERIMENT

A. Experimental Equipment and Purpose

The truck used in the experiment is shown in Fig.1. This truck has two SHACs which are the cooling devices combining with silencers to reduce the noise. The SHACs are connected to two ports of the blower by using the hoses as shown in Fig.2.

Fig. 1 High-Powered Suction Truck

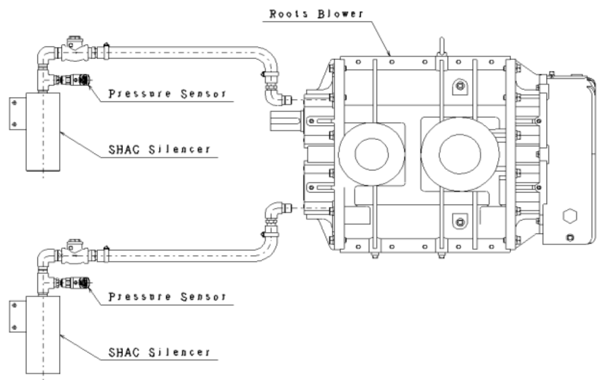

Fig. 2 Measuring Condition ①

As it is a clear fact that the noise source is a pressure fluctuation of the blower, it will be tried to use the interference type silencer by use of the phase difference of pressure fluctuations from two ports of the blower. The phase difference can be changed by use of the horses with the different length. The present study aims to clarify that this interference type silencer has the reduction effect of the noise.

B. Experimental Procedure

First, the pressure fluctuations from each port are measured as shown in Fig.2. This is named "measuring condition ①". Next, the phase difference between two pressure fluctuations from upper and lower ports of the blower is obtained and the hose length is adjusted as is obtained the opposite phase of the signals.

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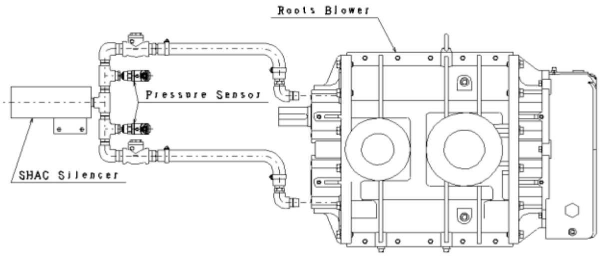

Fig. 3 Measuring Condition ②

Fig. 4 Photo of Measuring Condition ②

Lastly, the pressure wave form and the sound pressure level are measured after setting the SHAC with opposite phase as shown in Fig.3. This is named “measuring condition ②”.

The truck is operated at the condition that the total load is -96kPa and the rotating speed of the blower is 1500rpm. In the steady state, the fundamental frequency of the blower is $f=nN/60=6\times1580$rpm/60=158Hz and the fundamental frequency of the SHAC is 79Hz. Where n is 3×2=6. Because the number of the blower is 2 and each blower has 3 lobes.

It is necessary to make the phase difference between two pressure fluctuations opposite to reduce the noise. Therefore the length between two hoses is changed nothing but the half wave length of the target sound. As well the wave length can be obtained by the following expression.

$$\lambda = \frac{v}{f} \tag{1}$$

Where v is the sound speed and v=340m/s (At temperature 15 ℃).

In the case of targeting the fundamental frequency of the SHAC, its frequency and the wave length become f =79Hz andλ=4.3m respectively. As a result, the half wave length becomes 2.15m. And the timing of sucking down the air from two upper and lower ports has about 0.7m originally.

The difference of 1.45m is necessary to realize the opposite phase in the case of targeting the fundamental frequency of the SHAC. However it is difficult to realize it for a reason of the space. This time, we focus the ten times of the fundamental frequency of the SHAC of 790Hz. In this case, the targeting frequency and wave length become f =790Hz andλ=0.43m respectively. As taken into consideration the original phase difference 0.07m, the difference of hose length 145mm makes the opposite phase. In this study, it is examined whether the reduction effect of the noise can be achieved or not.

III. Experimental Results and Considerations

A. *Acoustic Simulations*

Fig.5 shows the measured result of pressure fluctuations at the measuring condition①. The green line shows the pressure wave measured at the upper port of the blower and the red line at the lower port respectively. This case was that the hose length of the upper port was 625mm and the length of the lower port was 500mm. The difference of length was 125mm. This length is a little shorter than 145mm of the target length. This difference is ignored here because of the two pressure fluctuation waves can be seen the waves with the opposite phase.

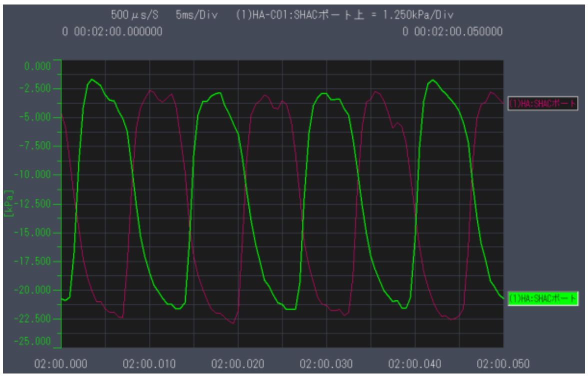

Fig. 5 Pressure Waves for Measuring Condition ①

Fig.6 shows the result of the measured pressure waves at the measuring condition ②. The green line and the red line show the results obtained at the upper and the lower port respectively. The two pressure fluctuation waves had the opposite phase as well as the result of ①.

The shapes of the pressure fluctuation were different from those of ①. It is due to the superposition of two fluctuations.

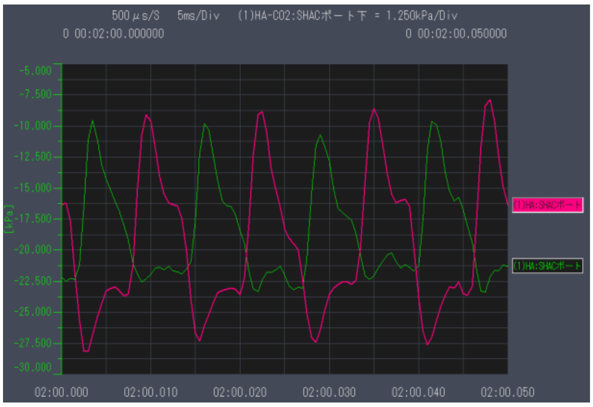

Fig. 6 Pressure Waves for Measuring Condition ②

Fig.7 shows the FFT results of the sound pressure level at the measuring conditions ① and ②. These sound pressure levels are measured at outlet of the SHAC. These are the results before (Red) and after (Green) the countermeasure.

O.A. values at the measuring condition ① and ② are 93.5dB and 89.1dB respectively. The reduction effect of 4.4dB could be achieved.

The component of the target frequency of 790Hz, it is the ten times of the fundamental frequency of the SHAC, can be reduced 15dB.

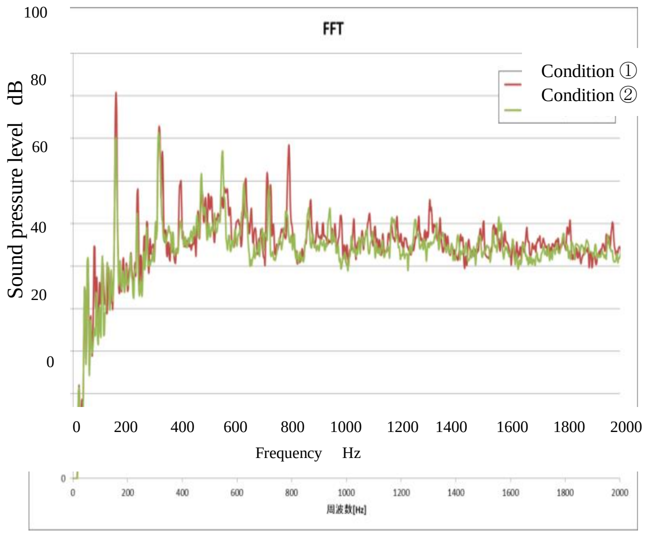

Fig. 7 Sound Pressure Levels at Condition ① and ②

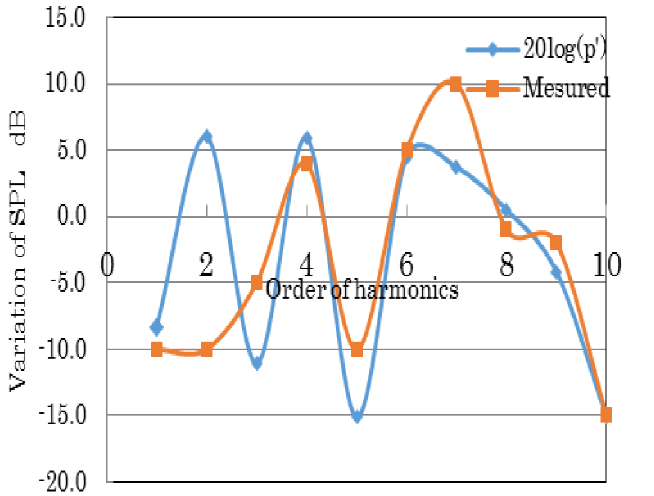

Fig. 8 Comparison between Prediction and Measured Data (Condition ②)

By the way, it can be seen from Fig.7 that there are effective part and non-effective part in reduction of these harmonic components. Then we will examine whether the result can be explained by only the phase difference of two pressure fluctuations or not. The two pressure fluctuations obtained at two ports are frequency analyzed and the phase difference φ of the both data is obtained. Denoting two pressure fluctuations $p_1(t)$, $P_2(t)$ and assuming the same amplitudes and denoting the fundamental angular frequency and the order number ω and n, respectively, the nth order component can be expressed as follows.

$$p_{1n}(t) = A_n \sin n\omega t, \quad P_{2n}(t) = A_n \sin(n\omega t - \phi_n)$$

Adding the both pressures,

$$p_n(t) = A_n \sin n\omega t + A_n \sin({}_n\omega t - \phi_n)$$

$$= A_n(\sin n\omega t + \sin n\omega t \cos\phi_n - \cos n\omega t \sin\phi_n)$$

$$= A_n(1+\cos\phi_n)\sin n\omega t - \sin\phi_n \cos n\omega t$$

$$A_n\sqrt{2+2\cos\phi_n} \cdot \sin(n\omega t - \psi_n) \qquad (2)$$

Where the amplitude and the phase are as follows.

$$A_n\sqrt{2+2\cos\phi_n} \qquad (3)$$

$$\psi_n = \tan^{-1}[\sin\phi_n/(1+\cos\phi_n)] \qquad (4)$$

$$L_p=20\log(p/p_0) \quad (p_0=2\times10^{-5}\text{ Pa}) \qquad (5)$$

The pressure amplitude p_n calculated by the expression (3) and the phase difference φ_n obtained the data at condition ②. p_n can be transformed by use of the Eq.(5) to obtain the sound pressure level L_p and it is compared with the reduction effect which are calculated by the measured sound pressure level of before and after the countermeasure as shown in Fig.8.

The both are comparatively in good agreement except one part (Especially second component). The pressure fluctuation, namely the sound pressure, can be evaluated by considering the phase difference. Especially, in the reduction effect of the target frequency component, the tenth component here, the prediction value is in good agreement with the measured value. The pressure fluctuation is one of the important causes of the noise but the noise is not determined by only the pressure fluctuation. The reason of the second component not agreeing with measured value, can be obtained from other except it. However it has not been clarified in the present stage.

Fig.9 shows the comparison of the SPL variation between the prediction and the measured data. The prediction data can be obtained by use of the pressure fluctuation at the condition ①. In this case, the both do not coincide with each other at all. The noise reduction can 't be achieved by use of the phase data before connection. It can be preferably clarified that the noise reduction can be achieved by use of the phase data after connection.

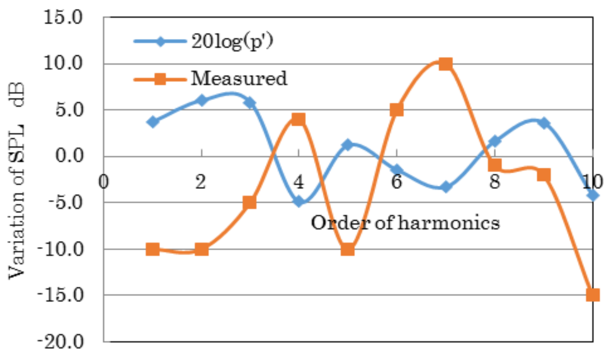

Fig. 9 Comparison between Prediction and Measured Data (Condition ①)

IV. Analysis Taken into Consideration of Amplitude Difference

A. *In the Case of Using Data after Connection*

Fig.10 shows the pressure fluctuation wave at upper port after connection and Fig.11 shows its frequency analyzing results. The fundamental frequency is 79Hz and many harmonics components can be seen in Fig.11. The pressure fluctuation wave and the frequency analyzing results can be obtained at the lower port as well as the upper port. The table1 shows the amplitudes and the phase difference between the both data at each order. Eq.(6) shows the pressure fluctuation superposed by two sine waves with different amplitudes. Where A_U and A_L are pressure fluctuation amplitudes of upper and lower ports respectively.

$$p_n(t) = A_U \sin n\omega t + A_L \sin(n\omega t - \phi_n) \quad (6)$$

As this expression can't become simpler than this, the amplitude after superposing will be obtained numerically. As one example, the result of the tenth order interested is shown in Fig.12 and the amplitude of the Eq.(6) is obtained.

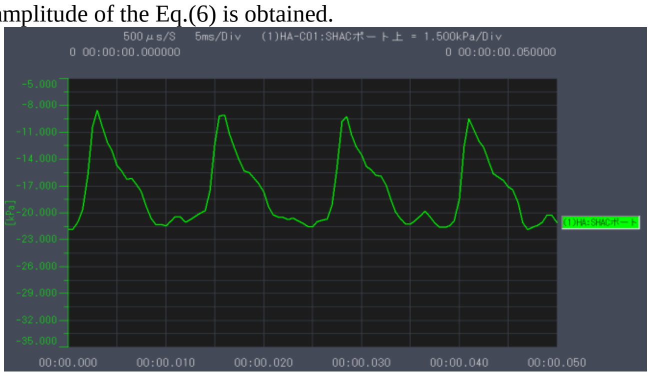

Fig. 10 Pressure Fluctuation of Upper Side in the Case of After Connection

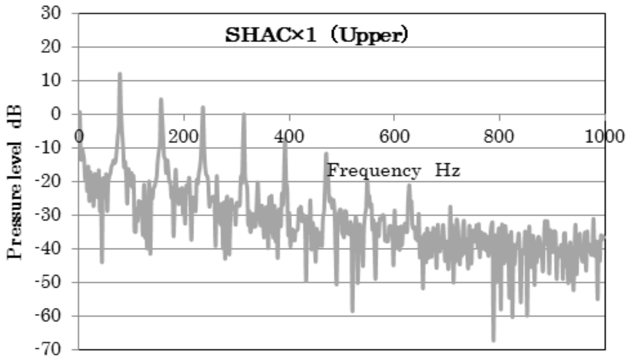

Fig. 11 Spectrum of Pressure Fluctuation of Upper Side in the Case of After Connection

These results are shown in “Connect” column in table2 and the reduction effect obtained from Fig.7 is shown in “Measured” column. The reduction effect can be obtained by the expression 20 log(p/p_0). Where p_0 and p are the “Power ave” and the “Connect” in table2, respectively.

The results obtained by use of Eq.(3) and the results of table1 are shown in table2. Where power ave. in table2 was obtained by Eq.(7).

$$p = \sqrt{P_{upper}^2 + p_{lower}^2} \quad (7)$$

Fig.13 shows the comparison of countermeasure's effect between the prediction and the measured data. The prediction value was obtained by the detail analysis. However the both are not in agreement at all in comparison with the simple analysis (Fig.8). Namely the improvement can not be seen.

Table1 Values in the case of using data after connection

Order	Freq. Hz	Upper kPa	Lower kPa	Dif. of Phsae
1	78	4.074	6.683	-158°
2	156	1.650	1.155	8.9°
3	236	1.296	2.489	-164°
4	314	0.994	0.743	16.3°
5	392	0.425	0.594	-170°
6	470	0.267	0.219	66°
7	548	0.106	0.072	-80°
8	628	0.091	0.091	116°
9	706	0.044	0.021	-144°
10	784	0.023	0.032	170°

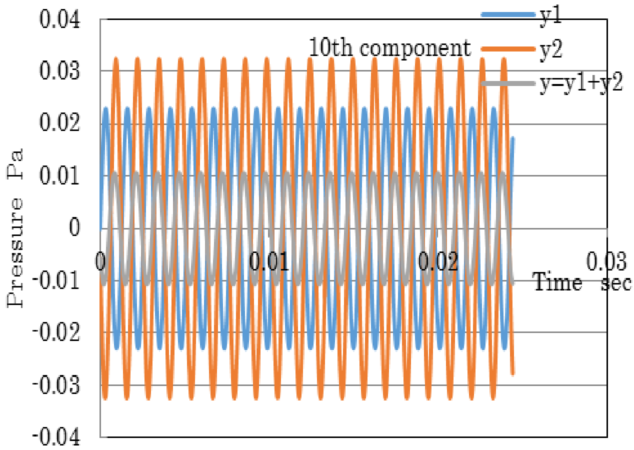

Fig. 12 Calculation Result of Fourth Component

Table2 Analytical result in the case of using data after connection

Order	Power ave.	Connect	20log(p/p0)	Measured dB
1	7.827	3.21	-7.7	-10
2	2.014	2.54	2.0	-10
3	2.806	1.135	-7.9	-5
4	1.241	0.28	-12.9	4
5	0.731	0.153	-13.6	-10
6	0.345	0.39	1.1	5
7	0.128	0.13	0.1	10
8	0.129	0.09	-3.1	-1
9	0.048	0.0185	-8.3	-2
10	0.040	0.0085	-13.4	-15

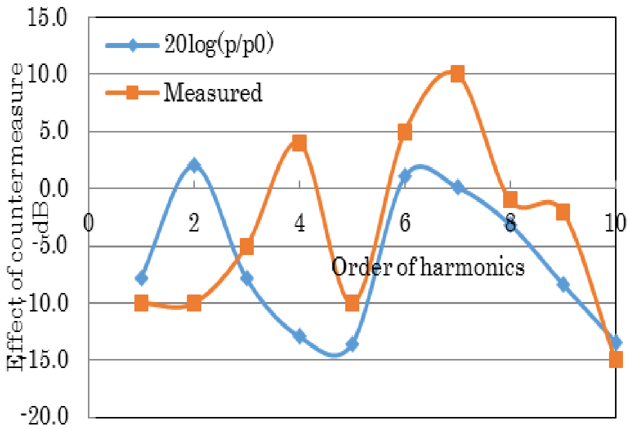

Fig. 13 Comparison between Prediction and Measured Data (Detailed Analysis)

B. In the Case of Using Data before Connection

The amplitude and the phase difference of two waves before connection are shown in table3.

The results obtained by using Eq.(6) and the data in table3 are shown in table4.

Fig.14 shows the comparison of countermeasure's effect between the detail analysis result and the measured data. But the both could not be seen the consistency.

From these analyses, it was clarified that the phase difference was more important than the amplitude in the prediction of the reduction effect.

Table3 Values in the case of using data before connection

Order	Freq. Hz	Upper kPa	Lower kPa	Dif. of Phsae
1	78	8.511	8.913	80°
2	158	1.346	0.961	3.6°
3	236	2.155	2.418	-22.3°
4	314	0.648	0.372	-147°
5	394	0.455	0.545	-110°
6	472	0.316	0.344	130°
7	550	0.240	0.174	-140°
8	628	0.127	0.083	106°
9	708	0.041	0.100	-81°
10	790	0.034	0.042	-144°

Table4 Analytical result in the case of using data before connection

Order	Power ave.	Connect	20log(p/p0)	Measured dB
1	12.324	13.34	0.7	-10
2	1.654	2.17	2.4	-10
3	3.239	4.16	2.2	-5
4	0.747	0.4	-5.4	4
5	0.710	0.54	-2.4	-10
6	0.467	0.262	-5.0	5
7	0.296	0.132	-7.0	10
8	0.152	0.126	-1.6	-1
9	0.108	0.105	-0.2	-2
10	0.054	0.0215	-8.0	-15

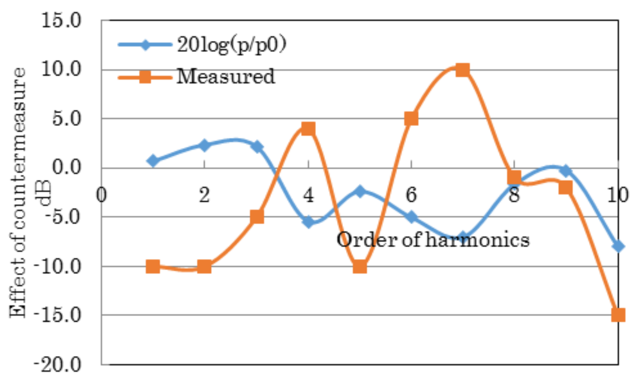

Fig. 14 Comparison between Prediction and Measured Data (Detailed Analysis)

C. Effect of Amplitude and Phase on Prediction Value

Fig.15 and Fig.16 show the comparison of pressure amplitudes from two ports (Upper and Lower) in before and after connection, respectively. The both are in good agreement with each other in before connection and it satisfies with the assumption of the same amplitude described before. On the other hand, the difference between two amplitudes can be seen in after connection and the assumption of the same amplitude does not come into existence.

Fig.17 shows the comparison of phase difference of pressure fluctuations from two ports (Upper and Lower) in before and after connection.

The both results are in good agreement over fifth order but not good under fifth order.

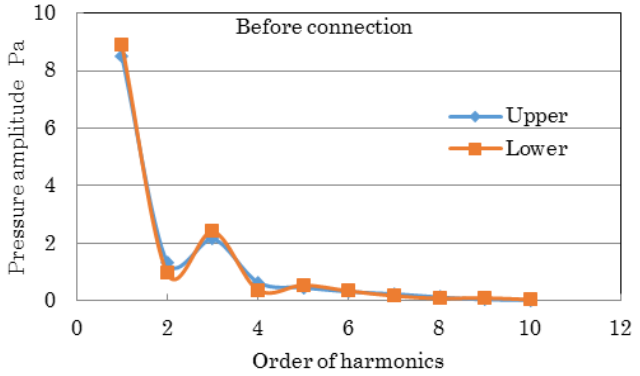

Fig. 15 Comparison between Upper and Lower Amplitudes Before Connection

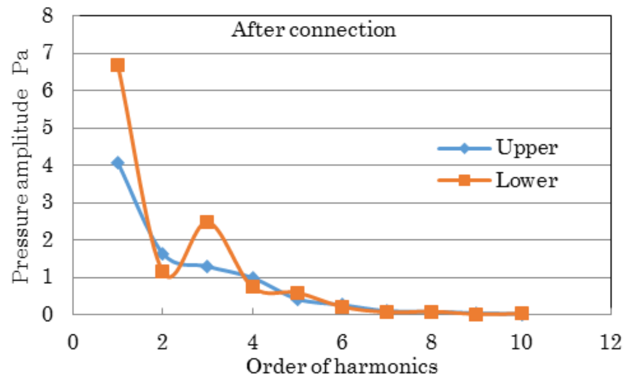

Fig. 16 Comparison between Upper and Lower Amplitudes After Connection

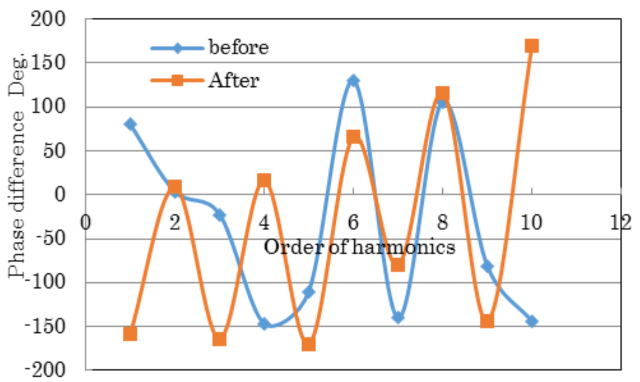

Fig. 17 Comparison between Phase Differences of Before and After Connection

D. Effect on Other Order When One Order is made Opposite Phase

It will be examined here how effect to othe order component has the tube length used for countermeasure of one order component. Assuming the target order being nth , the phase difference φ_n can be expressed like Eq.(8) because of half wave length.

$$\phi_n = j\omega_0 T_n / 2 = j\pi / n_0 \qquad (\because n\omega_0 T_n = 2\pi) \qquad (8)$$

Where ω_0 is the fundamental angular frequency. It is necessary to insert the tube with a half wave length into one side or the other side for the countermeasure

Next, we consider the case of superposing two pressure fluctuations. Assuming the same amplitude the expression becomes as follows.

$$p_j(t) = A_j \sin j\omega_0 t + A_j \sin j\omega_0 (t - T_n/2)$$
$$= 2A_j \sin\frac{j\omega_0 t + j\omega_0 t - j\omega T_n/2}{2}\cos\frac{j\omega_0 t - j\omega_0 t + j\omega T_n/2}{2}$$
$$= 2A_j \sin(j\omega_0 t - j\omega_0 T_n/4)\cos j\omega_0 T_n/4 \quad (9)$$

The amplitude can be given as follows.

$$2A_j \cos\frac{j\omega_0 T_n}{4} = 2A_j \cos\frac{j}{4}\left(\frac{2\pi}{n}\right) = 2A_j \cos\frac{j\pi}{2n} \quad (10)$$

Fig.18 shows the comparison between the results calculated by Eq.(10) and Eq.(6). The result by Eq.(10) is indicated by “analysis” and the result by Eq.(6) is indicated by “Theory” in Fig.18. Both results are in good agreement with each other as shown in Fig.18.

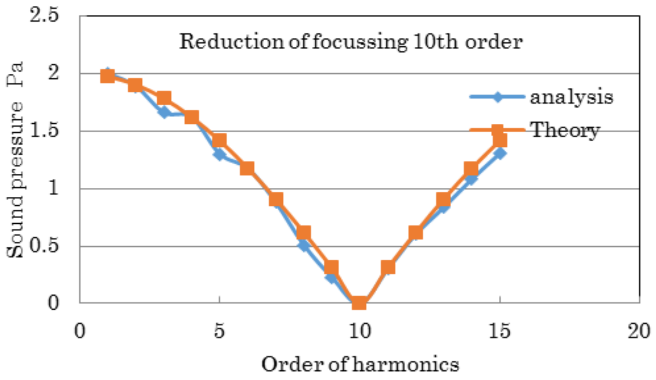

Fig.18 Comparison between Analysis and Theory Amplitudes

V. Conclusion

The interference type silencer is widely used to reduce the noise. In this study, this method is applied to the real high powered suction truck to reduce the noise. The results are as follows.

1) The noise reduction can be realized by use of the interference type silencer. In this study, we focus the tenth harmonics of the fundamental frequency of the SHAC, namely 790Hz and applied the interference type silencer to the real machine. As a result the reduction effect of 15dB can be achieved.

2) In SHAC silencer, the phase difference can be adjusted by changing two hose lengths .

3) It is better to use the pressure fluctuation after connection than that before connection for the prediction of the reduction effect.

4) This method leads cost down because of two SHACs reducing one SHAC

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