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THE IMPROVED ACTIVE CONTROL ALGORITHM FOR MARINE DIESEL TWO-STAGE VIBRATION ISOLATION SYSTEM

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Abstract

The active control technology was carried out on the marine diesel two-stage vibration isolation system (MDTVIS), the active control technology was able to make up for passive vibration isolation technology in low frequency range. The construction of the secondary path was one of the most important sectors, which had a full impact on active vibration isolation performance. Nonlinear components were comprised in the secondary path, which were principally the nonlinear vibration of multi-degrees of freedom in the practical MDTVIS system and nonlinear control path in the hydraulic servo actuator. The nonlinearity was not ignorable in coping with the second path, so that, the vibration isolation performance was greatly influenced by the secondary path in the active control technology with the classic adaptive comb-type filter. By combination the model reference adaptive inverse control strategy with the nonlinear robust control technology, the linearity control algorithm was designed, and then the classic adaptive comb-type filter algorithm was carried out for new system, herein the hybrid control strategy was constructed to applying to the secondary path in the practical MDTVIS system. The proposed hybrid control strategy was able to improve the initial active vibration isolation control algorithm with adaptive comb-type filter, and overcome shortcomings of the vibration strengthened in some multi-harmonic-frequency sites in low frequency range. The total performance of vibration isolation coupling with multi-path was improved in balance.

1. INTRODUCTION

As a power system of the shipping, marine diesel is main recourse of vibration, whose vibration spectrum relies on rotation speed of diesel, main object of diesel vibration isolation is to weaken the fundamental frequency vibration [1]. For discussing vibration isolation of marine diesel, marine diesel two-stage vibration isolation system (MDTVIS) is constructed.

About MDTVIS system, the more violent vibration is brought on the close end of diesel, and the weaker vibration on the output power end. So vibration isolation on the close end of diesel is dominating, and another end of MDTVIS is secondary. Active and passive vibration isolation technology is investigated on this type vibration of marine diesel of MDTVIS system.

Because marine diesel works on low-frequency range, active control technology become more important method applied on vibration isolation of that. The notch filter is designed by choosing an appropriate center-frequency, and the comb-type filter is constructed by seriating many a notch filter with distinct centre- frequency [1, 2]. The former is used to cope with fundamental-frequency vibration, and the latter for simultaneously considering fundamental- and harmonic vibrations. The MDTVIS system has some characters of complex structure, multi-degree of freedom vibration and hydraulic servo system as actuators, so nonlinearity is caused on the secondary path. Using adaptive comb-type filter algorithm, decrease of the fundamental frequency spectrum line is not ideal, but increase of harmonic spectrum lines is arisen on the diesel close end , and vibration on output power end is worsen. So, the adaptive comb-type filter algorithm is improved to apply to the MDTVIS system in the paper [3].

2. THE ADAPTIVE COMB-TYPE FILTER ALGORITHM, IMPROVEMENT AND IMPLEMENT

2.1 The adaptive comb-type filter algorithm

2.1.1 The notch filter algorithm

Adaptive notch filter has the structure of adaptive transversal filter as shown in Figure 1. So assuming adaptive transversal filter input X_k , time series is taken at the k th sampling time, with sampling frequency $f_s = 1/T$, where the i th element of filter input X_k with time index is

$$x_{ik} = C\cos(\omega_r kT + \theta_i) = C[e^{j\omega_r kT} e^{j\theta_i} + e^{-j\omega_r kT} e^{-j\theta_i}]/2 \tag{1}$$

θ_i is phase angle. Considering definition of $U(z) = 1/(z-1)$, the LMS algorithm $W_{i,k+1} = W_{i,k} + \alpha e_k x_{ik}$, the i th tap weight in Z-domain is

$$W_i(z) = \alpha C U(z)[E(ze^{-j\omega_r T})e^{j\theta_i} + E(ze^{j\omega_r T})e^{-j\theta_i}]/2 \tag{2}$$

Setting the time-dependant term

$$T_m = U(ze^{-j\omega_r T})E(ze^{-j\omega_r T})\sum_{i=1}^{N} e^{j2\theta_i} + U(ze^{j\omega_r T})E(ze^{j\omega_r T})\sum_{i=1}^{N} e^{-j2\theta_i} \tag{3}$$

and the window function

$$\beta(\omega_r T, N) = \sin(N\omega_r T)/\sin(\omega_r T) \tag{4}$$

Filter output signal is obtained in Z-domain

$$Y(z) = N\alpha C^2 E(z)[U(ze^{-j\omega_r T}) + U(ze^{j\omega_r T})]/4 + \alpha C^2 \beta(\omega_r T, N)T_m/4 \tag{5}$$

The time-dependant term is ignored in equation (5), when $\beta/N \approx 0$, so the transfer function of the open loop system, $R(z)$, is the output signal Z-transform, $Y(z)$, divided by the error signal

Z-transform, $E(z)$

$$R(z) = \frac{Y(z)}{E(z)} = \frac{N\alpha C^2[z\cos(\omega_r T) - 1]}{z^2 - 2z\cos(\omega_r T) + 1} \tag{6}$$

Where the poles are $z = e^{\pm j\omega_r T}$, zero is $z = 1/\cos(\omega_r T)$. The transfer function of close loop system, $Q(z)$, is given in Z-domain by

$$Q(z) = \frac{1}{1 + R(z)} = \frac{z^2 - 2z\cos(\omega_r T) + 1}{z^2 - 2(1 - N\alpha C^2/4)z\cos(\omega_r T) + (1 - N\alpha C^2/2)} \tag{7}$$

So zero of the transfer function, $Q(z)$ is pole of the transfer function, $R(z)$, i.e. $z = e^{\pm j\omega_r T}$. When the LMS algorithm has slow convergence, the value of $N\alpha C^2/4$ is far smaller than 1, the approximate pole location is

$$z \doteq (1 - N\alpha C^2/4)e^{\pm j\omega_r T} \tag{8}$$

The zero location is on unit circle, whose corresponding frequency is $\pm\omega_r$, and the pole location is inside of unit circle. So the notch filter at the frequency, ω_r, has infinite depth on the whole frequency domain[1].

2.1.2 Adaptive comb-type filter algorithm

The notch filter has a unique centre-frequency, so active control algorithm with the notch filter can handle single spectrum line of vibration. To handle the harmonic or multiple spectrum lines of vibration, several notch filter should used in the active control algorithm designing their corresponding centre-frequencies, thus the comb-type filter is constructed[2].

The comb-type filter includes many the notch filters. Obviously, the comb-type filter algorithm is induced as same as the notch filter.

Similar to equation (5), the output signal of the comb-type filter is described in Z-domain

$$Y(z) = \frac{N\alpha}{4}E(z)\sum_{m=1}^{M} C_m^2[U(ze^{-j\omega_m T}) + U(ze^{j\omega_m T}) + \sum_{m=1}^{M}\sum_{m=1}^{M}\frac{\alpha C_m C_n}{4}\beta(\frac{\omega_m - \omega_n}{2}T, N)T_m \tag{9}$$

the transfer function the open loop system, $R(z)$, is the output signal Z-transform, $Y(z)$, divided by the error signal Z-transform, $E(z)$

$$R(z) = \frac{Y(z)}{E(z)} = \frac{N\alpha}{4}\sum_{m=1}^{M} C_m^2[U(ze^{-j\omega_m T}) + U(ze^{j\omega_m T})] \tag{10}$$

and then the transfer function of the close loop system, $Q(z)$, is given in Z-domain by

$$Q(z) = \frac{1}{1 + R(z)} = \frac{1}{1 + \frac{N\alpha}{4}\sum_{m=1}^{M} C_m^2[U(ze^{-j\omega_m T}) + U(ze^{j\omega_m T})]} \tag{11}$$

The comb-type filter has all of the advantage of the notch filter, except needing more memory space and run time of computer. Each centre-frequency of the comb-type filter is designed by equation (10). The bandwidth of the centre-frequency can be designed by adjusting parameters of N , α , T in equation (10).

2.2 Model reference adaptive inverse control with pre-compensator algorithm

The almost nonlinear dynamic system in engineering applications can be described by equation (1). The function of $f(r,y)$ can be approximated by finite-dimension polynomial simply. So the approximate depiction of the system will be obtained [3].

$$y = H(s)r + f(r,y) \tag{12}$$

The nonlinear system (12) should be linearity control to its linear transfer function $H(s)$ by employing the Model reference adaptive inverse control with pre-compensator algorithm [1]. The PCMRAIC algorithm is shown in Figure.1. The pre-compensator $G(n)$ is designed for the aimed nonlinear system $P(n)$ in frequency domain. $H_m(n)$ is the reference model.

If the nonlinear dynamic system is autonomic, and approximately depicted by the Volterra series form as follows,

$$y(t) = \sum_{n=1}^{\infty} \int_{-\infty}^{+\infty} \cdots \int_{-\infty}^{+\infty} h_n(\tau_1, \cdots, \tau_n) \prod_{i=1}^{n} u(t-\tau_i) d\tau_i \tag{13}$$

Where, the n-order Volterra kernel, $h_n(\tau_1, \cdots \tau_n)$, is the n-order general impulse response function, and then, the n-dimension Fourier transform of that is defined as n-order general frequency response function (GFRF)

$$\hat{h}_n(\omega_1, \cdots, \omega_n) = \int_{-\infty}^{+\infty} \cdots \int_{-\infty}^{+\infty} h_n(\tau_1, \cdots, \tau_n) e^{j(\omega_1\tau_1 + \cdots + \omega_n\tau_n)} d\tau_1 \cdots d\tau_n \tag{14}$$

The n-order GFRF of the aimed system, $\hat{p}_n(\omega_1,,\omega_n)$,is obtained by the definition (14) in equation(12).If n-order GFRF of the destination system $\hat{h}_n(\omega_1, \cdots, \omega_n) \doteq 0$ when $\forall n \geq 2$ and $\hat{h}_1(\omega) \triangleq H(s)\big|_{s=j\omega}$, the n-order GFRF of the compensator, $\hat{g}_n(\omega_1,,\omega_n)$, can be calculated by $\hat{h}_n(\cdot) = \hat{g}_n(\cdot) \cdot \hat{p}_n(\cdot)$. So the pre-compensator, $G(s)$, can be easily derived by H_∞ control theory[3]. And the pre-compensator as the estimator or predictor, is helpful to the algorithm convergence.

The general adaptive control algorithm fails to deal with the nonlinear system, and neither does the x-filtered adaptive control algorithm[4,5].Because the nonlinear dynamic system does not meet the superposition theory, the aimed system can not be exchanged with the filter. However, the problem is solved by the adaptive inverse control. It is feasible of some adaptive inverse control handling with the system (12). Moreover, it is inevitable that the nonlinear dynamic system (1) has some certain the inverse model [5].

As above, the PCMRAIC algorithm is designed. The PCMRAIC algorithm is the linearity control strategy as a whole, and it is feasible strategy to effetely handle the nonlinear system [1].

2.3 The proposed hybrid control strategy

If the aimed system is nonlinear system, the linear system theory and control algorithm become a little appropriate. The nonlinear system theory and control algorithm should be employed to the aimed nonlinear system. Therefore, the linearity control is carried out on the aimed nonlinear system using the PCMRAIC algorithm, and then the ordinary notch filter or the comb-type filter can be applied to the linearization system for active control strategy, so the hybrid control strategy is proposed as shown in Figure 1.

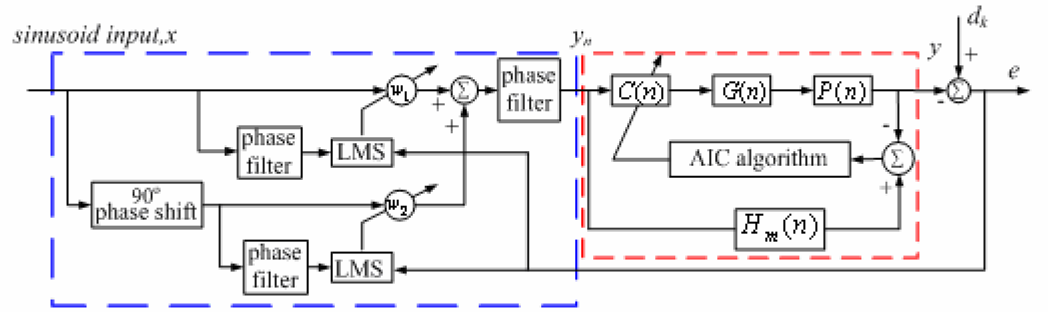

Figure 1. Block diagram of the proposed hybrid control strategy: adaptive notch filter algorithm (inside the left blue block) and the PCMRAIC algorithm (inside the right red block).

3. ADAPTIVE VIBRATION ISOLATION ON MDTVIS SYSTEM

3.1 MDTVIS system

Vibration spectrum of the marine diesel relies on diesel's rotation speed, for discussing vibration isolation of this, so marine diesel two-stage vibration isolation system (MDTVIS) is constructed. The MDTVIS system is shown in Figure 2, which include the mechanics part, e.g. marine diesel, power meter, the common mounting, actuators, medium-masses, isolator accelerometers, and the electrics part, e.g. industry computer, electric charge amplifiers, band pass filters, accelerometers, DSP of TMS320VC33 and the corresponding emulator.

The common mounting and all of structure above are looked on as a whole, so-called upper mass system. To equipped four actuators, the medium mass system is divided into four identical mass arranged respectively on four corners under the common mounting, the medium mass is connect to the found base by isolator. Each identical mass is as the measuring point equipped with accelerometer. Measuring point 1 and 2 is arranged on the close end of marine diesel, another two measuring points (No3 and No4) on the power output end.

The actuator is an important component in active control. The hydraulic servo system is employed, which include hydraulic pump, four-path servo controller, electric-hydraulic servo valve, hydraulic cylinder and displacement transducer. The actuator is paralleled with the isolator and connected between the upper mass system and medium mass.

3.2 The secondary path

To active control of vibration on the MDTVIS system, the hydraulic servo system is used as actuator, which employs displacement feedback control. So there are two distinct control paths. one is the control path of actuator as defined above, and another path is the secondary path, which is composed of DSP, four-path servo controller, electric-hydraulic servo valve, hydraulic cylinder, medium mass, accelerometer, electric discharge amplifier band pass filter and DSP.

Nonlinearity is introduced into the secondary path, considering viscous friction stress in electric-hydraulic servo valve, and hydraulic oil flux fluctuates because of unsteady load, 3-degree of freedom coupling vibration of marine diesel as well. Harmonic spectrum lines exist on the acceleration response, and vibration isolation of the MDTVIS system is affected greatly. Therefore, the PCMRAIC algorithm is proposed to carry out the nonlinearity control on the secondary path, and then the adaptive comb-type filter is employed to eliminate the fundamental spectrum line of vibration of marine diesel.

3.3 Adaptive control strategy proposed on MDTVIS system

Four-path acceleration signals are picked up by accelerometers arranged on the measuring points, respectively. As the cost function of active control, four-path acceleration signals are comprehensively considered, the cost function are minimized by employing active vibration control strategy, so vibration isolation of the MDTVIS system is realized.

According to control theory above, the hybrid control strategy is applied for the MDTVIS system as shown in figure 1. Some points are emphasized: the aimed nonlinear system $P(n)$ is one of the GFRFs of the secondary path, the reference model, $H_m(n)$, is obtained by nonlinear system identification technology. The MDTVIS system is uncoupled by divided the medium mass system into four identical mass, and each control path of actuator is controlled on its own path. Therefore, to active vibration isolation of the practical MDTVIS system, four identical control methods are simultaneously realized.

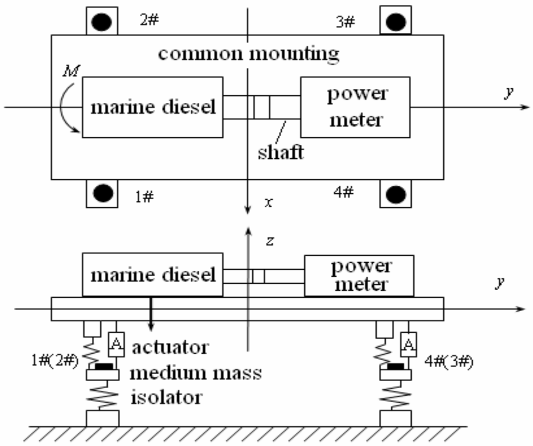

Figure 2. Schematic diagram of the MDTVIS system: the picture of the practical system (left) and the structure diagram of the practical system's (right).

4. EXPERIMENTAL STUDY

All of the discrete time acceleration signals on measuring points are obtained with sampling frequency of 1000Hz. The acceleration spectrum is given by Hanning window function and Fourier transform on the original discrete time signals. The fundamental frequency is the rotation speed divided by constant quantity of 30, because the diesel is 4-stroke, 4-cylinder engine.

Experiments of active control of vibration using the proposed algorithm are implemented on the MDTVIS system when diesel works at 1000-1700r/min. The results of experiments are similar in the whole experimental frequency band. So the result diagram of diesel working at 1201r/min is given in figure 3 and 4. For harmonic vibration existing in the acceleration response, nonlinearity is verified in the secondary path. Of the MDTVIS system, vibration of the diesel close end is main, which has the bigger quantity level than one of the power output end. The fundamental frequency vibration is eliminated using the proposed control algorithm except that harmonic vibration is strengthened on measuring point 2and 4.

Contrast experiments between the proposed control algorithm and active comb-type algorithm are implemented on the MDTVIS system as shown in figure 5 and 6. The former algorithm has better performance than the latter one in handling fundamental frequency vibration. The former algorithm leads to less harmonic vibration than the latter except for measuring point 1. The maximum decrease of vibration isolation reaches to 24dB using the proposed algorithm, 14dB relatively to the adaptive comb-type algorithm.

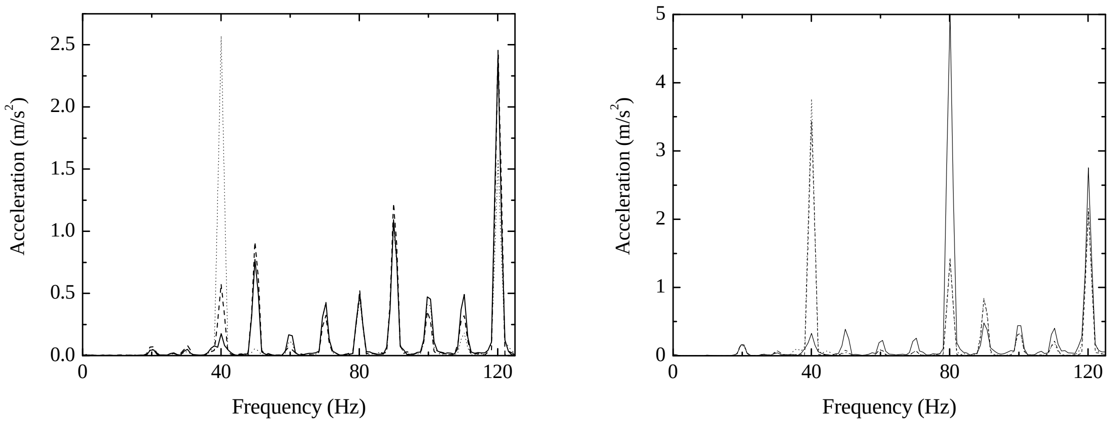

Figure 3. Acceleration response of the diesel close end (measuring point 1:left and measuring point 2: right) with different vibration isolation control algorithm while diesel working at 1201r/min: without control (· · · ·), the comb-type filter algorithm (– – – -) and the proposed hybrid control algorithm (——).

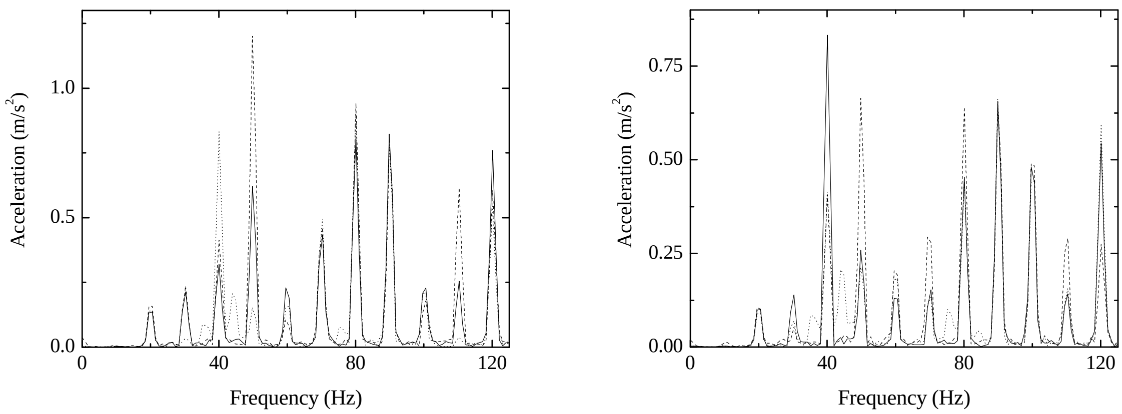

Figure 4. Acceleration response of the power output end (measuring point 3: left, measuring point 4: right) with different vibration isolation control algorithm while diesel working at 1201r/min: without control (· · · ·), the comb-type filter algorithm (– – – -) and the proposed hybrid control algorithm (——).

5. CONCLUSIONS

Considering nonlinearity of the secondary path of the MDTVIS system, the hybrid control strategy is proposed by combining the adaptive comb-type filter algorithm and the PCMRAIC algorithm. Experiments of active control of vibration on the MDTVIS system are implemented. Some conclusions are drawn. The proposed control algorithm is more appropriated strategy for the fundamental frequency vibration isolation than the linear control algorithm e.g. the comb-type filter algorithm. Of marine diesel, vibration relying on rotation speed should be eliminated by the proposed control strategy. To handle harmonic vibration, improvement of the proposed control strategy is little made. Therefore, more work should be done further, such as nonlinear system identification of the secondary path, a detailed analysis of parameters of the proposed control strategy.

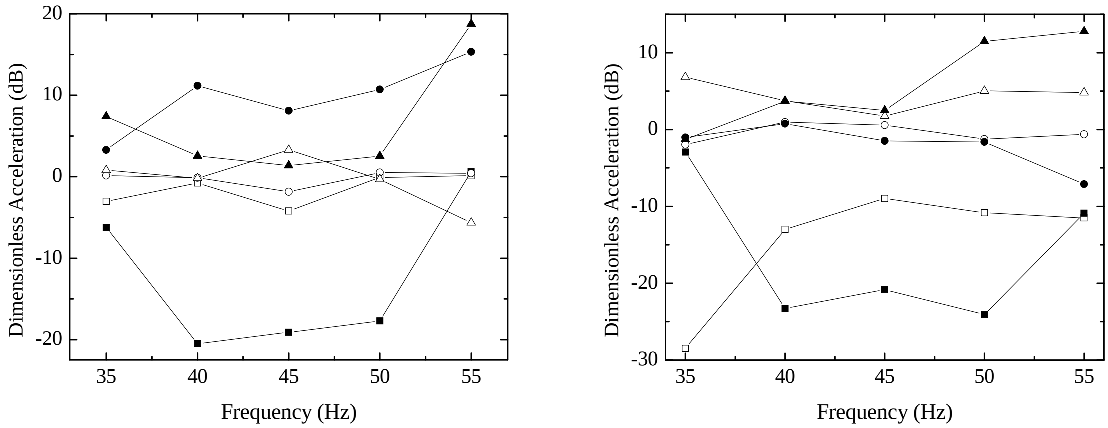

Figure 5. Decrease of acceleration of the diesel close end (measuring point 1:left and measuring point 2: right): 1st order using comb-type algorithm (–□–), 1st order using improved algorithm (–■–), 2nd order using comb-type algorithm (–○–), 2nd order using improved algorithm (–●–), 3rd order using comb-type algorithm (–△–) and 3rd order using improved algorithm (–▲–).

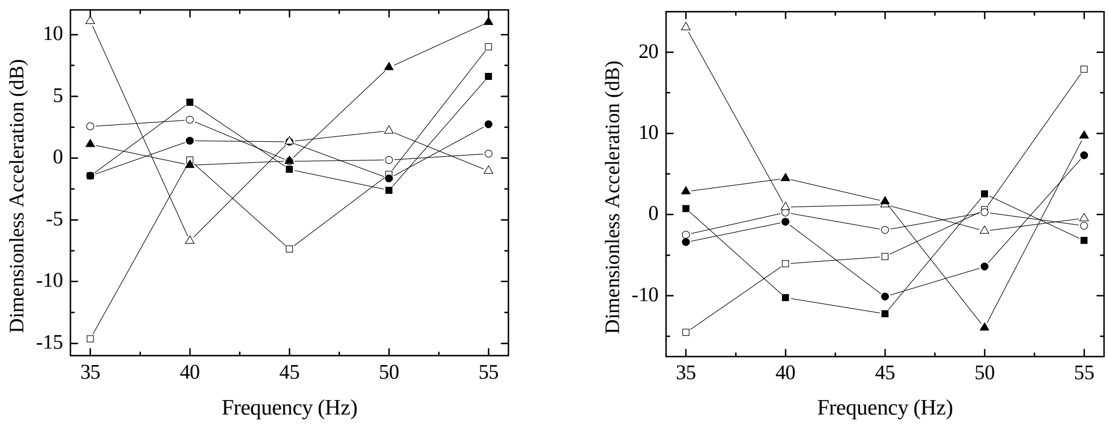

Figure 6. Decrease of acceleration of the power output end (measuring point 3: left, measuring point 4:right): 1st order using comb-type algorithm (–□–), 1st order using improved algorithm (–■–), 2nd order using comb-type algorithm (–○–), 2nd order using improved algorithm (–●–), 3rd order using comb-type algorithm (–△–) and 3rd order using improved algorithm (–▲–).

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