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Articles

Measurement of booster pump vibration in a hemodialysis machine and assessment of operational status by Fast Fourier Transform analysis

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I. Introduction

Maintenance procedures based on the bathtub curve concept incorporate the idea of time-based maintenance (TBM), in which the longer a device is used, the more likely it is that each component will wear out and the more likely the device is to malfunction. Therefore, devices should be overhauled and components should be replaced after a certain amount of time has elapsed to prevent them from malfunctioning[1)].

For medical devices, revisions to the Medical Care Act published by the Japanese Ministry of Health, Labour and Welfare in March 2007 oblige medical institutions to formulate maintenance inspection plans for specified medical devices and to implement such inspections[2)]. When formulating maintenance inspection plans, according to the Guidelines for the Formulation of Plans for Maintenance Inspections of Medical Devices and the Appropriate Conduct of Maintenance Inspection (version 1.02) published by the Japan Association for Clinical Engineers, the frequency of regular inspections may be defined either in terms of device operating time measured by a device operation timer or in terms of calendar time, such as once every three months or once yearly[3)].

However, since the speed with which individual devices wear out will vary depending on how they are used, formulating a maintenance inspection and component replacement plan based solely on operating or use time may result in discrepancies with the most suitable times for maintenance, inspection, and component replacement, thereby reducing efficiency. The problem also remains that even if TBM has been implemented, operational errors or incompetence may cause early malfunctions after maintenance inspections[4)].

We have previously reported that device diagnostics using vibration measurements were capable of detecting the wear state of the duplex pump of a hemodialysis machine and that measuring the vibration of each component of the device could provide an indicator for the most appropriate maintenance inspection and component

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replacement times. Here, it should be noted that the individual manufacturers of hemodialysis machines recommend that components be replaced depending on elapsed operating times as part of their maintenance procedures and that Japanese Industrial Standards (JIS) Z 8115[5], which covers reliability terms, also embraces the TBM concept. However, TBM can be inefficient if preventive maintenance is performed too early or too late, and malfunctions due to operational mistakes during maintenance inspections can also present problems[1].

With these points in mind, this study explores the use of vibration measurement as a condition-based method of assessing the operating state of a booster pump, which is one of the structural components of hemodialysis machines. More specifically, we investigate its value via confirmatory testing after a maintenance inspection to minimize the introduction of early malfunctions that might be caused by operational mistakes or incompetence.

II. Experimental Methods

We first adjusted the tightness of a bolt in the booster pump of a DBB-73 hemodialysis machine (Nikkiso Co., Ltd., Japan) to simulate an operational error during a maintenance inspection. The repair and maintenance inspection manual states that the bolt should be tightened during maintenance inspections while a balance is being achieved; the fastening torque is not specified[6].

In this study, the bolt was first tightened by a clinical engineer with 20 years' experience, and this tightness level was taken as the reference value. We then defined three pump vibration measurement conditions as (a) reference, (b) loose, or (c) overtight, depending on whether the bolt was tightened to this reference value, loosened from it, or overtightened.

We then fit a vibration sensor to the center of the anterior cover of the booster pump, which has a rotational speed of 2200 rpm when the fluid flowing through is water. Finally, the displacement (DISP), velocity (VEL), acceleration (ACC) were obtained as voltage (V) using a DIGI-VIBRO Model 1332B digital vibration meter (Showa Sokki Co., Ltd., Japan) and a VIBRO recorder Model 9801 vibration waveform recorder (Showa Sokki Co., Ltd., Japan), with the measurement mode set to AUTO and vibration sampling time from 1 μs to 10 ms.

The vibration measurement data thus obtained were used for Fast Fourier Transformation (FFT) analysis carried out using Model-9803-90 FFT analysis software (Showa Sokki Co., Ltd.).

III. Results

1. Vibration measurements

Figures 1 to 9 show the voltages recorded at the pump under each condition. The mean voltages recorded at the booster pump were compared for DISP, VEL, and ACC under conditions (a), (b), and (c). For DISP, the vibration amplitude, expressed as the mean ± standard deviation (maximum, minimum), was (a) 0.0024 ± 0.00079 V (0.0042 V, 0.0006 V), (b) 0.00013 ± 0.0092 V (0.0406 V, −0.0312 V), and (c) 0.00009 ± 0.01 V (0.0286 V, −0.0397 V).

A t-test showed significant differences between (a) and (b) and between (a) and (c) ($p < 0.05$), but the difference between (b) and (c) was not significant. Greater vibration amplitude occurred under conditions (b) and (c) compared with (a). For VEL, the vibration amplitude, expressed as the mean ± standard deviation (maximum, minimum), was (a) 0.01342 ± 0.005 V (0.025 V, 0.005 V), (b) −0.00029 ± 0.004 V (0.0144 V, −0.0125 V), and (c) −0.00376 ± 0.066 V (0.121 V, −0.14 V).

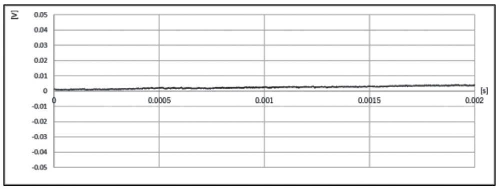

Fig. 1 DISP vibration measurement, reference

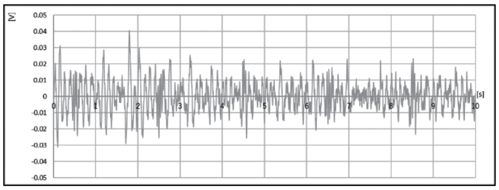

Fig. 2 DISP vibration measurement, loose

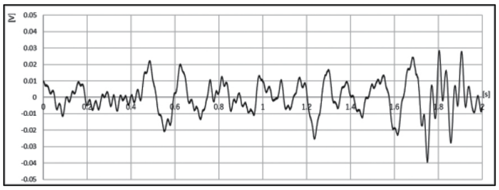

Fig. 3 DISP vibration measurement, overtight

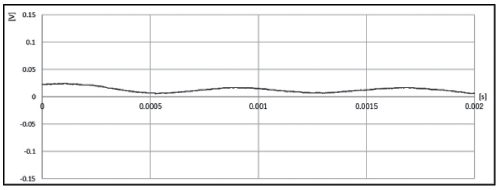

Fig. 4 VEL vibration measurement, reference

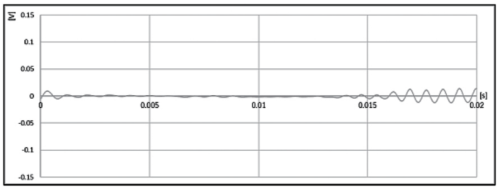

Fig. 5 VEL vibration measurement, loose

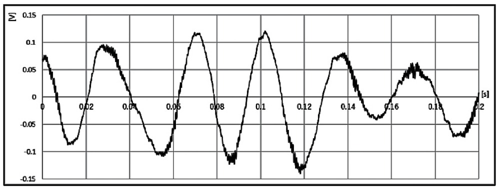

Fig. 6 VEL vibration measurement, overtight

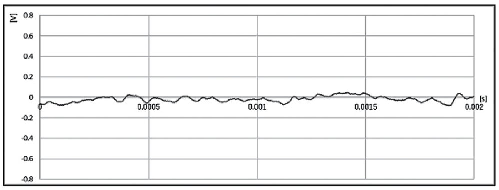

Fig. 7 ACC vibration measurement, reference

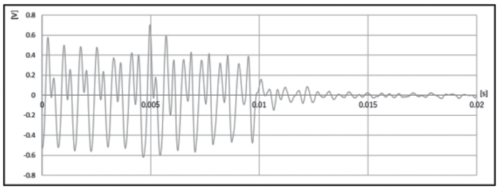

Fig. 8 ACC vibration measurement, loose

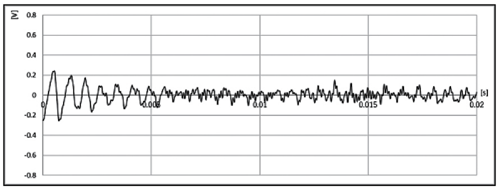

Fig. 9 ACC vibration measurement, overtight

A t-test showed significant differences between (a) and (b), (a) and (c), and (b) and (c) ($p < 0.05$). The vibration amplitude increased in the order (a) < (b) < (c). For ACC, the vibration amplitude, expressed as the mean ± standard deviation (maximum, minimum), was (a) −0.0174 ± 0.028 V (0.047 V, −0.08 V), (b) −0.0021 V ± 0.22 (0.704, −0.62 V), and (c) 0.0025 ± 0.064 V (0.243 V, −0.255 V). A t-test showed significant differences between (a) and (b), (a) and (c), and (b) and (c) ($p < 0.05$). The vibration amplitude was larger for (b) and (c) than for (a).

2. FFT analysis

FFT analysis of the vibration data from the pump under each condition was performed. The results are shown in ***Figures 10 to 12***. For DISP, the peak frequency: amplitude value was (a) 976.56 Hz: 0.0019 V, (b) 8789.0 Hz: 0.0068 V, and (c) 64453.1 Hz: 0.0047 V. For VEL, the peak frequency: amplitude value was (a) 976.56 Hz: 0.0078 V, (b) 976.56 Hz: 0.0011 V, and (c) 4882.8

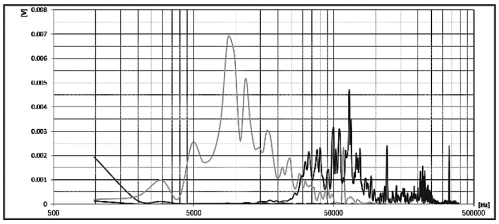

Fig. 10 DISP FFT analysis

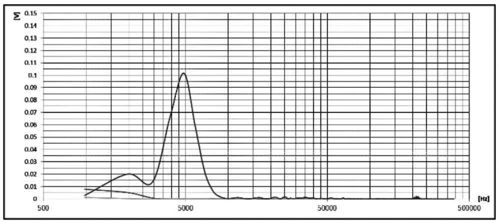

Fig. 11 VEL FFT analysis

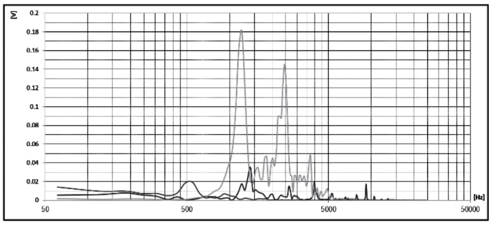

Fig. 12 ACC FFT analysis

Hz: 0.1018 V. For ACC, the peak frequency: amplitude value was (a) 549.31 Hz: 0.0189 V, (b) 1220.70 Hz: 0.181 V, and (c) 1403.81 Hz: 0.020 V.

IV. Discussion

DISP measurements show the actual distance traveled by the vibrating part. Under condition (b), the peak-to-peak distance and SD were greater than under condition (a). This may have been because the impeller inside the booster pump and the pump cover vibrated more strongly as a result of the bolt loosening. Under condition (c), peak-to-peak distance and SD were also greater than under condition (a). This may have been because the overtightened bolt meant that the vibration of the impeller was transmitted to the cover.

There were significant differences in DISP measurements between (a) and (b) and between (a) and (c), but the difference between (b) and (c) was not significant. The reason for this could not be precisely identified, but the fact that significant differences were evident from the reference condition suggested that DISP measurement may offer a simple method of detecting abnormalities.

VEL measurements express the velocity of vibration. Under condition (b), the overall vibration amplitude was smaller and the cycle was not constant, with a number of cycles evident. This may have been because loosening the bolt made it more difficult to sense the vibration of the impeller and other components, or because the vibration from the impeller was conducted to the cover more easily at some times and less easily at others. Contrary to the difference between (a) and (b), under condition (c) the overall vibration amplitude was stronger and the cycle was almost uniform. This may have been because overtightening the bolt caused the vibration speed of the impeller to be detected more efficiently.

ACC measurements express changes in velocity per unit time. Under condition (b), compared with (a) the vibration amplitude was larger at some times and smaller at others, as was also evident for the difference in VEL measurements between (a) and (b). This similarly suggests that there were times when the vibration was not conducted as efficiently as it was at other times.

It is also possible that greater impact force may have been generated at times when the vibration amplitude was larger. Under condition (c), the vibration amplitude was still larger than for (a) although it was smaller than for (b), thus suggesting that the impact force may have been greater. This may have been because overtightening the bolt limited the movement of the impeller, thereby imposing a strain during rotation.

The DISP values obtained from vibrometry are unrelated to frequency, but VEL is proportional to frequency, and ACC is proportional to the frequency square. Since these frequency differences cause changes in specific measurement parameters, caution is required when analyzing vibration measurements. The parameters calculated from the signals obtained from vibrometry are usually described as “feature parameters,” and are divided into dimensional and non-dimensional feature parameters[7].

In this study, we measured the pump vibration under different conditions. Because the vibrometry data is comprised of dimensional parameters, distinguishing the causes of different abnormalities is infeasible. However, our results suggest that it may be possible to use DISP, VEL, and ACC measurements (or combinations of these measurements) to determine whether there is anything wrong with the booster pump.

FFT analysis showed that for DISP and VEL, the peak frequency was only 976.56 Hz under condition (a). This result validates the hypothesis that under stable operating conditions, a consistent intrinsic vibration is generated. For ACC measurements, however, the peak frequency was different, and this will be a subject for further research. Very large vibration with DISP measurements of ≥ 5000 Hz was detected in (b) and (c). Because the actual vibration amplitude is greater than in (a), over the long term this might cause a malfunction to occur.

In the VEL measurements, misalignment may have caused the impeller vibration seen in (c), thereby suggesting that overtightening the bolt may have caused deformation between the impeller and the booster pump motor axle. For the ACC measurements, the peak frequency was around 1000 Hz under all the pump conditions. This was considered to be due to gear and impeller vibrations, with the amount of vibration particularly large under conditions (b) and (c).

Frequency analysis via FFT analysis enables the vibration characteristics generated to be assessed, and repeated measurements and their analyses may enable the detection of abnormalities.

V. Conclusion

In the vibrometry measurements of a medical device conducted in this study, we detected the different vibrations generated by a booster pump depending on its condition and found that an analysis of the measured values enabled the determination of whether or not a hemodialysis machine could be used. We also identified the possibility of discovering abnormalities that could result in malfunctions after long-term use, thereby suggesting that vibrometry may be useful in the maintenance of medical devices.

[References]

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