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Noise reduction of dry vacuum pump using the boundary element method to model impeller blade passage frequency

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ABSTRACT

Acoustic field analysis was conducted to propose noise reduction measures for the suction housing of a vacuum pump used in dentistry. The target frequency for reduction was selected by measuring the sound pressure level during steady-state operation, allowing identification of the primary noise sources through intensity and vibration measurements. The impeller area was analyzed by designing a full-scale analytic model for sound field analysis using reverse engineering, including precise 3D modeling. The inner boundaries were then separately extracted to complete a model for acoustic analysis. The characteristics of the inner suction housing area were analyzed using the Boundary Element Method (BEM). Noise reduction measures were proposed by analyzing the characteristics of the suction housing with respect to the differences in excitation frequency brought about by changing the number of impeller blades used. The acoustic frequency response function (FRF) of the inner suction housing was obtained by applying BEM. The relationships between the suction housing and the noise source were investigated to propose noise reduction measures. The proposed measure of reducing impeller blade number was validated by showing that it would avoid resonance in the suction housing by moving the BPF to a lower frequency. Thus, this study proposed the reduction of the number of impeller blades to reduce the noise of the current suction housing design considerably while maintaining its performance.

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1. Introduction

The suction housing is a device essential in dentistry; it allows the patient's airway to be maintained despite the large amounts of debris and secretions that can be generated in the oral cavity during treatment. During operation, suction housings often generate 70 dB(A) of noise, and can generate 80 dB(A) or higher in some cases. This noise is a source of stress for dentists and hygienists, and can make patients fearful and anxious. For these reasons, dentists as consumers are increasingly demanding improvements to the suction housing in terms of reducing noise. A number of studies have been conducted since the 1930s regarding the aerodynamic noise caused by the impeller in the suction housing, including studies by Madison [1] and Deming [2]; most such studies since the 1990s have used computational fluid dynamics (CFD) because of computational advances in this area [3,4]. Some researchers have conducted studies on the reduction of noise in centrifugal fans and blowers, but most of these have focused on noise prediction and flow analysis using CFD. Therefore, further studies must be carried out from the point of view of noise reduction, including the prediction of actual noise and evaluation of noise emitted by the noise source [5–9]. Meanwhile, additional analytical studies of the aerodynamic noise caused by the impeller also need to be conducted that integrate the two fields of fluid dynamics and acoustics. Most of the suction housing's apparent noise is generated when the aerodynamic noise generated by the impeller is emitted outside [10,11]. The exhaust pipe is also one of main noise sources of the suction housing. For the exhaust pipe, the use of a silencer is quite useful, offering noise reduction that is quite economical in terms of cost and production availability. The silencer's noise reduction performance can be quantified easily by calculating the transmission loss using the transfer matrix method [12]. Thus, conducting acoustic analysis of the aerodynamic noise caused by the impeller and studying the silencer's exhaust noise reduction is an effective way to identify opportunities for noise reduction. In general, it is expensive to manufacture prototypes for verification after the design of low-noise impellers. For this

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reason, acoustic analysis of impellers is often carried out using 3-D modeling [13–18]. In addition, the design drawing is created using CAD and the mass production is based on CAM. Product research also requires computer-assisted analysis, including consideration of the difficulties of actual reproduction; this work entails a great deal of time and expense. In this computer analysis, the most basic and important task is modeling. If the researcher wishes to obtain analytic results quickly, the analysis can be reduced by simplifying aspects that do not strongly affect the result. However, simplifying the wrong shape will cause erroneous results; thus, the researcher carrying out the modeling needs to have appropriate engineering knowledge. Thus, modeling work is important during design and mass production, as well as during analysis. In the present work, reverse engineering was used to carry out modeling for an analytic object, making precise analysis possible by allowing the design of an exact model [19–21]. Reverse engineering is widely used across many industries, including healthcare, manufacturing, construction, and civil engineering.

The purpose of this study was to identify the noise sources and noise characteristics of the suction housing, and to acoustically analyze the noise source to identify noise reduction measures. For this purpose, measurements of sound pressure, vibration, and intensity were collected during normal, steady-state operation of the suction housing. Then, the presence or absence of resonance was determined by comparison with the BPF that was identified through the process of measuring the sound pressure level. Detailed 3D modeling was conducted using reverse engineering, allowing a model for acoustic analysis to be designed by extracting the inner boundaries separately after the 3D modeling was conducted. For the modeling of an analytic object using the reverse engineering, an analytic model was designed that was exactly consistent with the full-scale one, allowing more accurate analysis. In particular, the acoustic FRF inside the suction housing was obtained by applying BEM. The characteristics of the acoustic FRF in the suction housing were identified by varying the number of impeller blades. Noise reduction measures were proposed by analyzing the noise characteristics of the suction housing with respect to the excitation frequency for the different numbers of impeller blades modeled. The proposed measures avoided resonance in the suction housing by reducing the BPF through reduction of the number of impeller blades. The effects of the blade number upon the noise characteristics and performance of the suction housing were investigated. The acoustic characteristics of the suction housing interior were analyzed using BEM. A noise reduction measure was proposed by analyzing the characteristics of the different FRFs resulting from the use of different numbers of impeller blades. A key analysis informing the proposed noise reduction measure was an inner field analysis conducted using various excitation sources.

2. Experimental apparatuses and methods

2.1. Sound pressure measurement

Noise sound pressure level was measured by using a microphone (B&K Type 4198) placed 1 m in front and 1 m above the suction housing during its normal operation. The time domain signal of sound pressure was transformed to frequency domain data by using fast Fourier transformation (FFT), carried out using a FFT analyzer (B&K 3560B-040). Experimental apparatuses and measurement methods are shown in Fig. 1. Time-series data were collected up to the maximum frequency of 10 kHz by using a FFT analyzer.

2.2. Sound intensity measurement

The sound intensity is a vector quantity indicating both the magnitude and direction of the acoustic energy. The sound intensity is influenced fairly little by background noise, and thus is useful for finding the sources of noise. In this study, sound intensity was measured in the front and the rear; on both sides; and on the top of the suction housing during its normal operation (Fig. 2). The sound intensity probe kit (B&K Type 3595) was used to measure intensity. The probe kit includes the 1/2 in. sound intensity microphone pair enabling 1/3-octave centre frequency measurements between 20 Hz and 6.3 kHz. The two microphone signals were analyzed using a frequency analyzer, and then only the values of the imaginary part were stored among the cross spectrum values of the two signals in the monitoring PC. Sound intensities were calculated using a computer and the results were visualized as 2-D contours. Sound intensity was measured by applying 3200 Hz as f_{max} to identify the noise level at 3000 Hz, the blade passage frequency. In general, the size of microphone and spacer

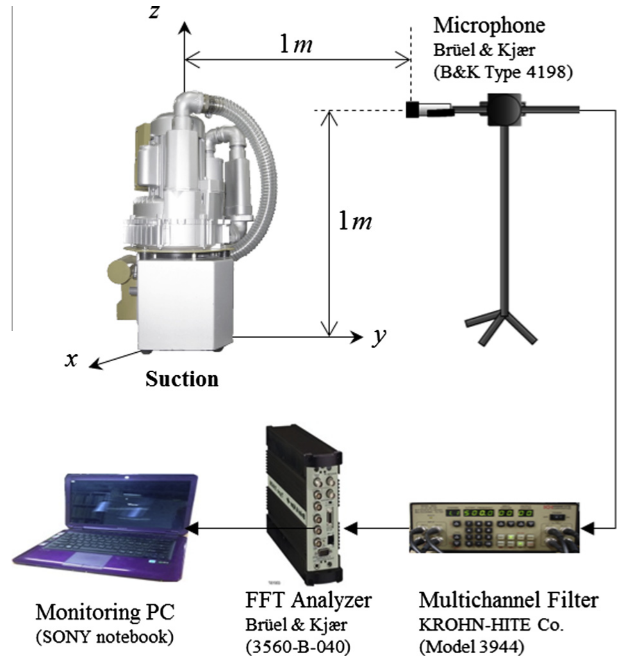

Fig. 1. Measurement of suction sound pressure.

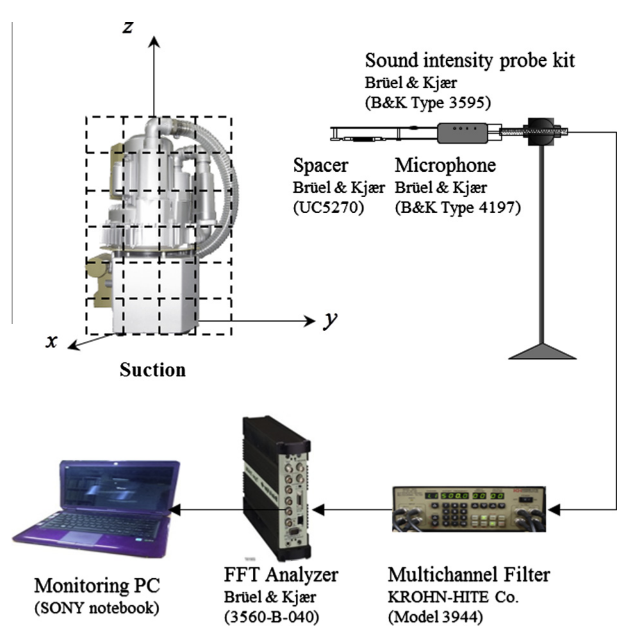

Fig. 2. Intensity measurement and analysis system.

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