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Centrifugal fan with inclined blades for vacuum cleaner motor

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ABSTRACT

Centrifugal fans have several technical applications. Their aerodynamic performance is well-optimized nowadays, but the same does not apply to their acoustic performance. Noise control studies of centrifugal fans are often focused on designed operating conditions or operating conditions close to the onset of instability. This paper seeks to find an alternative geometry of the centrifugal fan impeller which would improve noise control of centrifugal fans in a wide range of operating conditions. In this paper, the term noise control refers to noise level reduction and additionally to manipulating the psychoacoustic properties of noise.

The experimental work and numerical calculations focus on the centrifugal fan in vacuum cleaners. The experimental work, based on numerical simulations, is described to investigate the influence of the triangular cross section on the flow channel, formed by two inclined blades in opposite directions, on aerodynamic properties and the psychoacoustic performance of the impeller. The study demonstrates that impellers with a triangular flow channel achieve an aerodynamic performance which is comparable to that of standard impellers. The results also show that impellers with inclined blades deliver superior results in psychoacoustic metrics compared to impellers with upright blades.

1. Introduction

The noise generated by vacuum cleaners is the most recognizable noise source among all household appliances with a suction unit as the dominant source of noise. The suction unit is an original equipment manufacturer product, assembled from an electric motor, an impeller and a protective cover, forming a vaneless diffuser and airflow channels. Quieter and less annoying vacuum cleaners can be designed only by installing quieter and less annoying suction units; performing noise control measures on the suction unit itself is therefore inevitable. The dominant source of noise in the suction unit is its impeller and this study therefore focuses on noise control of the impeller. In this paper, the term noise control refers to noise level reduction and additionally to manipulating the psychoacoustic properties of noise.

The suction unit generates noise due to its vibrating surfaces (vibration-induced noise) and due to pressure pulsations in the airflow (aerodynamically generated noise). The level of vibration-induced noise and the level of flow-induced noise are comparable to the same type of noise levels in large fans. In the case of small and medium-sized fans, which are the main focus of this paper, aerodynamically generated noise is dominant [1]. The level of vibration-induced noise in a suction unit is typically at least 10 dB lower than the level of aerodynamically generated noise, making the latter the dominant source of noise in any suction unit [2]. Aerodynamically generated noise has both tonal and broadband characteristics. Discrete or narrowband tonal noise is correlated with rotation and the blade passing frequency (BPF), along with its higher harmonics. Turbulent noise is characterized by a broadband frequency spectrum [3].

Tonal noise is usually the dominant element of the total noise level and the main disturbing aspect of noise. Tones are produced as a result of regular cyclic motion of the fan's blades with respect to a stationary observer, and by interacting with adjacent structures [4,5]. Flow interactions between the impeller and the volute casing cause periodic pressure fluctuations on the impeller's solid walls and casing. These periodic pressure fluctuations are the sources of aerodynamic tonal noise radiation, mathematically described by dipole sources, as well as periodic structural vibrations resulting in tonal noise [6].

Reduction of the tonal noise level with BPF is essential for overall noise control and for reducing the irritating character of suction unit noise. Scientists have long been concerned with this problem and several diverse solutions have already been proposed. Neise summarized the methods for noise reduction of the centrifugal fan and proposed the following: (1) increasing cut-off clearance, (2) increasing the radius of the cut-off edge's curvature, (3) increasing the angle of inclination between the impeller's blades and cut-off edge, (4) staggering the blades of double inlet or double row impellers, (5) mounting wire meshes along the inner and outer circumference of the radial blade row, (6) irregular blade spacing, (7) mismatch between the acoustic

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impedances of the fan and duct system, (8) a triangular guide belt around the impeller, (9) rectangular fan casing, (10) circular fan casing, (11) acoustically optimized fan casing, (12) optimum annular clearance between the impeller's eye and intake nozzle, (13) acoustic lining of the fan's interior casing, (14) using the minima of the fan's acoustic radiation efficiency, and (15) resonators at the cut-off edge. His work [7,8] presents a milestone in subsequent research on noise control of centrifugal fans.

The experimental and numerical results of the study by Q. Liu confirmed that a slight increase in the distance between the impeller tip and the volute tongue, and a moderate slope of the volute tongue could also considerably reduced the noise in the investigated centrifugal fan [9]. Hayashi experimentally investigated the influence of an inducer placed at the inlet of the centrifugal fan impeller. Its efficiency was improved; however, this had practically no effect on the noise levels. The result of the experiment confirmed that noise is generated at the tip of the blades and the influence of the blade's angle on the outlet was therefore investigated further. Researchers concluded that a lower outlet blade angle reduced the velocity fluctuation of the wake, resulting in lower noise levels [10]. Bayomi also experimented with noise reduction by controlling the inflow onto the centrifugal impeller with flow straighteners. He reported a reduced noise level by 3 dB with backward curved blades and a slight reduction in efficiency as a side effect [11]. Boltežar thoroughly analysed the effect of uneven blade spacing [5]. Irregular fan blade spacing had no significant effect on the unweighted total sound pressure level (SPL) or the cooling capacity of the radial fan. However, a significant dispersion of the sound power over several harmonics was found because of irregular fan blade spacing, thus allowing a reduction of the siren effect. As a result, the tonal aspect of noise radiated by the fan which had been optimized for specific operating conditions would generally disappear in unavoidable broadband noise [5]. An uneven set of blade angels was also patented. Experience showed that such a blade configuration poses vibration problems due to a more complex balancing procedure. Additionally, such a configuration generates higher harmonics of BPF while producing noise with a high tonality, although the level of noise at BPF is reduced.

Further development of low noise centrifugal fans focused on the modification of impeller and guide vane geometry, based on an analysis of computational fluid dynamics (CFD) and computational aeroacoustic (CAA) simulations. Examples of such an approach are: (1) suppressing tonal noise in a centrifugal fan by implementing guide vanes on the fan outlet instead of diffuser vanes [12,13], (2) implementing a vaned diffuser with a partial height relative to the height of the blades [14], (3) implementing an inclined leading edge on the vaned diffuser [15,16], (4) splitting the tip of the flow channel by adding additional blades [17], (5) a tapered impeller with inclined blades [18], (6) chamfering the top of the blades with S-shapes [19], and (7) elongating the blade and increasing its wrap angle [20].

Paramasivam focused on the interaction between impeller blades and guide vane blades. By changing the geometry of vane blades so that they would work as guide channels instead of diffusers, he reduced the noise level by 6.8 dB at BPF [12,13]. Zhang and Gong numerically and experimentally investigated the influence of vaned diffusers on noise. They showed that applying half of the vane diffuser's height remarkably reduced overall fan noise in the wide operating range. The optimal height of the half vane h/b was 0.6, while larger heights increased fan noise. The performance of a fan with half vane diffusers improved at high flow rates, while it slightly worsened at low flow rates in comparison to the original fan. The half vane diffuser additionally extended into the operating range. Fan noise could be reduced by both increasing the radial gap and using a half vane, but their effects were not additive [15]. Researchers also found that replacing the diffuser with guide vanes led to noise reduction. They further reported an improvement in fan performance along with noise reduction by changing the geometry of vane blades, i.e. inclining their leading edge [14–16]. A similar approach of tapering the trailing edge of impeller blades was also considered by Jeon [18]. To reduce the high tonal sound generated by the aerodynamic interaction, designs of an unevenly pitched impeller (blade outlet angle), diffuser and tapered impeller were proposed and the experiments carried out. This reduced the flow interaction between the rotating impeller and the stationary diffuser due to some phase shifts. The uneven pitch design of the impeller changed the sound quality, while the overall SPL and performance remained comparable. Seung applied a design concept of inclined S-shaped trailing edge lines; the broadband self-noise decreased by using these edge lines and inducing a phase difference among the sources of broadband self-noise on the trailing edge line, as well as among the sources of tonal noise. Fans with the inclined S-shaped trailing edge were confirmed by numerical analyses of their noise performance, in which hybrid CAA techniques were adopted. The tonal noise at BPF was found to be reduced by approximately 2–7 dB in comparison to existing fans and that higher reductions could be achieved with larger inclination angles [19]. Scheit et al. experimentally and numerically confirmed a dominant jet-wake flow pattern, unsteady in nature, on the outlet from the impeller. The pattern emerged due to the vortex formation and blockage of the blade channel, causing high velocities on the pressure side of the blade. They concluded that low velocities on the suction side of the adjacent blade channel influenced a shear flow, forming a secondary flow, and disturbing the flow in the adjacent channel. Due to this interaction, the disturbances propagated from channel to channel established an unsteady flow pattern which led to pressure fluctuations on the blade surfaces, and thus resulted in noise generation. Such phenomena have already been reported as sound generation due to rotating stall. By increasing the wrap angle and keeping other geometric parameters constant, the flow was better guided in the blade passage, which led to a clear reduction in the size of vertical structures. This consequently reduced streamline fluctuations in the blade passage and pressure fluctuations on the blade surface, yielding reduced acoustic radiation compared to the impeller with a smaller wrap angle. This was found to be true for all investigated flow rates [20].

Numerical simulations and advanced measurement techniques helped pinpointing the location of the dominant noise source in centrifugal fans for vacuum cleaners. It lies between the rotating impeller and the stationary diffuser/leading edge of vane blades, where aerodynamic interaction between the two parts is most intense. Previous studies have contributed to understanding the role of guide blades and vanes in tonal noise generation. However, the majority of the reported research was focused on designed operation conditions (DOCs). If a broader operating range is taken into account, omitting the diffuser or guide vanes may be considered. The omission of stationary vanes leads to an increase of non-rotational turbulent noise, as a result of the high velocity of the flow leaving the impeller [12,13]. Yet this is only the case if the fan runs at DOCs. If the fan operates outside of DOCs, the airflow hits the vane blade at a non-ideal angle, which results in reduced efficiency and higher noise levels [21]. Pressure pulsations in this area depend on the operating condition and the aerodynamics of the centrifugal fan should therefore be optimized for a wider operating range [22].

Alternative possibilities of centrifugal fan noise control have also been proposed in recent years, among them the Active Noise Control [23–27]: the implementation of open cell metal foam [28,29] and a psychoacoustic approach to fan design with the purpose of reducing the annoyance of its noise [30,31]. The objective in psychoacoustics is to find a metric that allows an evaluation of the sounds' annoyance or pleasantness belonging to a special technical noise class without performing extensive hearing comparison measurements. Such an approach is well-accepted in the automotive industry. The idea of using psychoacoustic metrics for the development of centrifugal fan impellers was adopted into our work and is presented in this paper. Few studies reported on analysing the psychoacoustics of centrifugal fans, but none of them used this analysis as a tool during the design stage of the