Comparative acoustic study of electromagnetic actuator technologies used in haptic applications

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Introduction

Haptic technologies are currently experiencing an steeped interest, with companies such as Meta increasing their investment into developing what has been named the "Metaverse", where both the physical and virtual realities converge [1]. However, such endeavor requires multiple prior developments, being one of the main bottlenecks in that regard the current state of haptic interfaces. The progress in that regard has been so far considerable, but there are multiple challenges and aspects that remain unsolved, due to the wide range of requirements.

When analysing haptic design research with focus on haptic gloves, various functional aspects are analysed, ranging from power consumption to stimuli generation, amongst multiple others, however acoustic specifications are missing in such analyses. Examples of such omission are seen in haptic surveys [2][3], or in developed products, such as the first version of Dexmo glove [4]. Even in more recent publications focused on improving already commercial haptic devices [5], numerous ergonomic, functional and user oriented aspects are taken into account, except for acoustics, which remains unmentioned.

In this work, the acoustic annoyance of various actuators suitable for force feedback in haptic applications is analysed. This paper is based on previous work [6], where five different motors were analysed with regard to their annoyance perception. Three different technologies were analysed: stepper motors, servomotors, and geared DC motors. In such work, annoyance perception tests were realised, observing that the stepper motor presented low annoyance values and the geared DC motors high values, while servomotors caused a more diverse response, depending on the speed of their motion. As the stepper motor presented in such case low speed and torque capabilities, and the DC motors high noise, the focus lies here on servomotor annoyance analysis and comparison.

For such goal, the sound of various servomotors has been measured under various load conditions, their A weighted sound pressure level (SPL) [7] extracted, and an annoyance perception experiment with test subjects has been executed and analysed. These various aspects will be explained in detail in the following sections.

Measurement setup

For this analysis, six servomotors, shown in Fig. 1, have been used, namely: AMEWI 922MG, Blue Bird BMS101DMG, Blue Bird BMS115HV, DFRobot DF9GMS, Master DS708 and MKS DS6125e. They were selected taking into account the need of a compact and lightweight actuator system in haptic gloves. For that reason, most of them present a compact design, except the DS6125e, which presents a slightly higher volume (23 x 12 x 27.25 mm) and weight (21.21 grams). Their features can be visualized in table 1. Another additional detail is that the minimum supply voltage was 4.8 V for almost all of them (5 V applied in experimental setup), except for the BMS115HV, which requires 6 V.

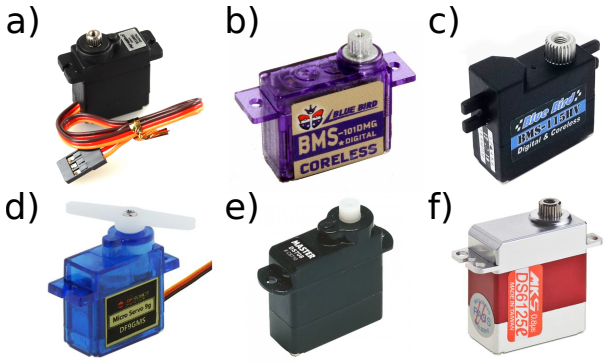

Figure 1: Servomotors used in this work: a)AMEWI 922MG b)Blue Bird BMS101DMG c)Blue Bird BMS115HV d)DFRobot DF9GMS e)Master DS708 F)MKS DS6125e.

As seen in table 1, there is no mention to the acoustic sound levels of the actuators or any other acoustic features, which could prove useful in user oriented applications. Therefore, in order to analyze their perception on haptic applications from an acoustic perspective, a testbench for sound measurement is prepared, as shown in Fig. 2. However, first the motion of the actuators must be defined. Force feedback in haptic applications is a complex issue, as in an ideal haptic device the motor system should be able to perform both static and dynamic forces, capable of various velocities and impedances in the second case. Therefore, due to the wide range of possible motions and forces, in this experiment these are narrowed down to a simple, more specific case. Here, the test conditions are constrained to the application of a load force

Table 1: Technical features of the servomotors. Response times are detailed for a motion of 60 degrees, except for the DS708, where it's for 45º.

Motor	Voltage [V]	Stall torque [kg·cm]	Response time [s]	Weight [g]	Dimension [mm]	Price [€]
922MG	4.8	1.8	0.1	12	23.2 x 12 x 30	15.99
BMS101	4.8	0.8	0.09	4.4	18.6 x 7.6 x 15.7	22.99
BMS115	6	4.3	0.13	11.3	23.2 x 10 x 23	18.99
DF9GMS	4.8	1.2	0.12	9	22.6 x 12.2 x 30	3 - 4
DS708	4.8	0.5	0.08	4.5	20 x 8 x 22	9.95
DS6125e	4.8	2.58	0.066	21.21	23 x 12 x 27.25	80.99

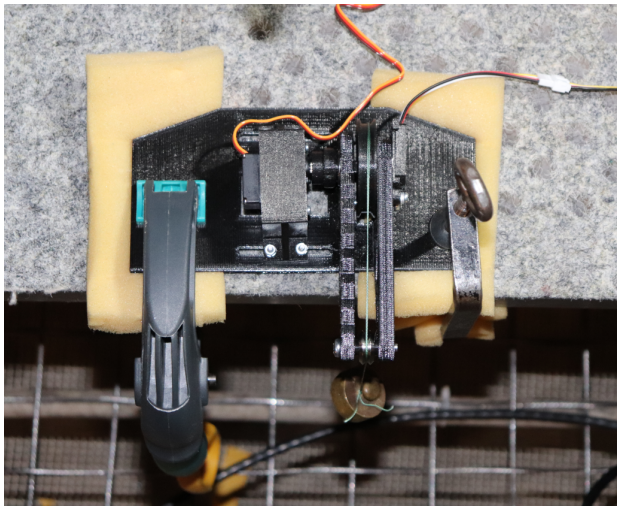

Figure 2: Base structure for load lifting with interchangeable servomotors.

in a single rotation direction.

For that goal, the test bench is designed with a pulley mechanism, where different loads can be attached to the actuator, which should perform lifting, followed subsequently by a dropping motion, holding at all times the load. Such structure allows testing of various actuators. For this experiment, 3 different loads are selected: 50, 100 and 200 grams, and the radius of the motor pulley is 20 mm. Therefore, minimum required torque values would be 0.1, 0.2 and 0.4 Kg·cm respectively. With regard to the executed motion, a 60 degree motion forward and backwards is chosen, being recorded twice per recording.

These various conditions, 18 in total, were recorded in the anechoic chamber located at the TU Dresden's facilities, with a calibrated Microphone B&K, type 2671, and a SQUADRIGA II recording system from HEAD acoustics. As the focus is on haptics, and therefore on devices that would be relatively close to the head, a distance of 200 mm is chosen between the sound source and the microphone, as shown in Fig. 3. The motion of the actuators, pulling and pushing twice the correponding load, were recorded, presenting each recording a total duration of 8 seconds. Additionally, in order to reduce vibration propagation, foam material was placed in every contact area between the various structural parts, that means, between the test bench, the table and the microphone holder.

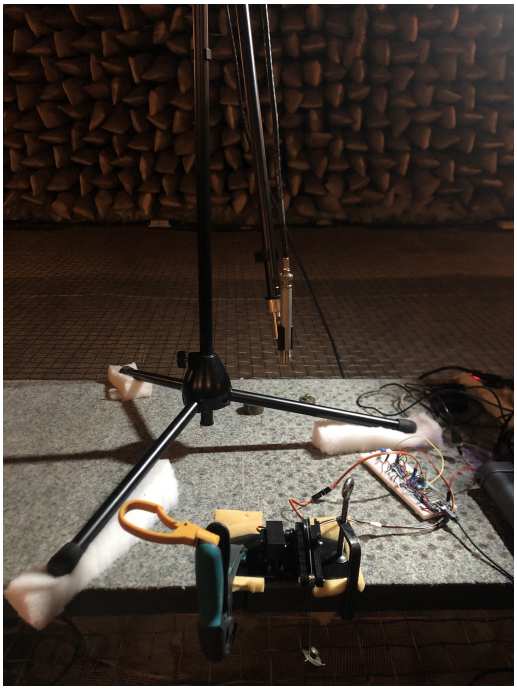

Figure 3: Measurement setup for motor sound acquisition at the anechoic chamber of TU Dresden.

Annoyance perception test

In total 18 sounds were recorded and used in the posterior perception test with 18 subjects, 14 male and 4 female, ranging from 25 to 41 years old. The sound reproduction system consists of Beyerdynamic DT990 headphones, with their volume adjusted in signal level to the original sound recordings. For every test subject there are 6 training sounds, one sound per type of actuator. After the training, they listen to 3 repetitions of each sample, which accounts in total to 54 sounds, presented in a randomized order. A semantic differential test was used for the annoyance experiment, where 5 labels were shown, ranging from *nicht*, meaning not annoying, to *sehr*, which is extremely annoying. The user's semantic rating is saved as a value between 0 (*nicht*) and 100 (*sehr*).

In Fig. 4 the A weighted sound pressure levels (SPL) versus time for each case are shown, alongside the corresponding mean annoyance value displayed in green. Sounds are divided in 6 groups according to the actuator in use, organized in each group by weight from left to right, that is 50, 100 and 200 grams.

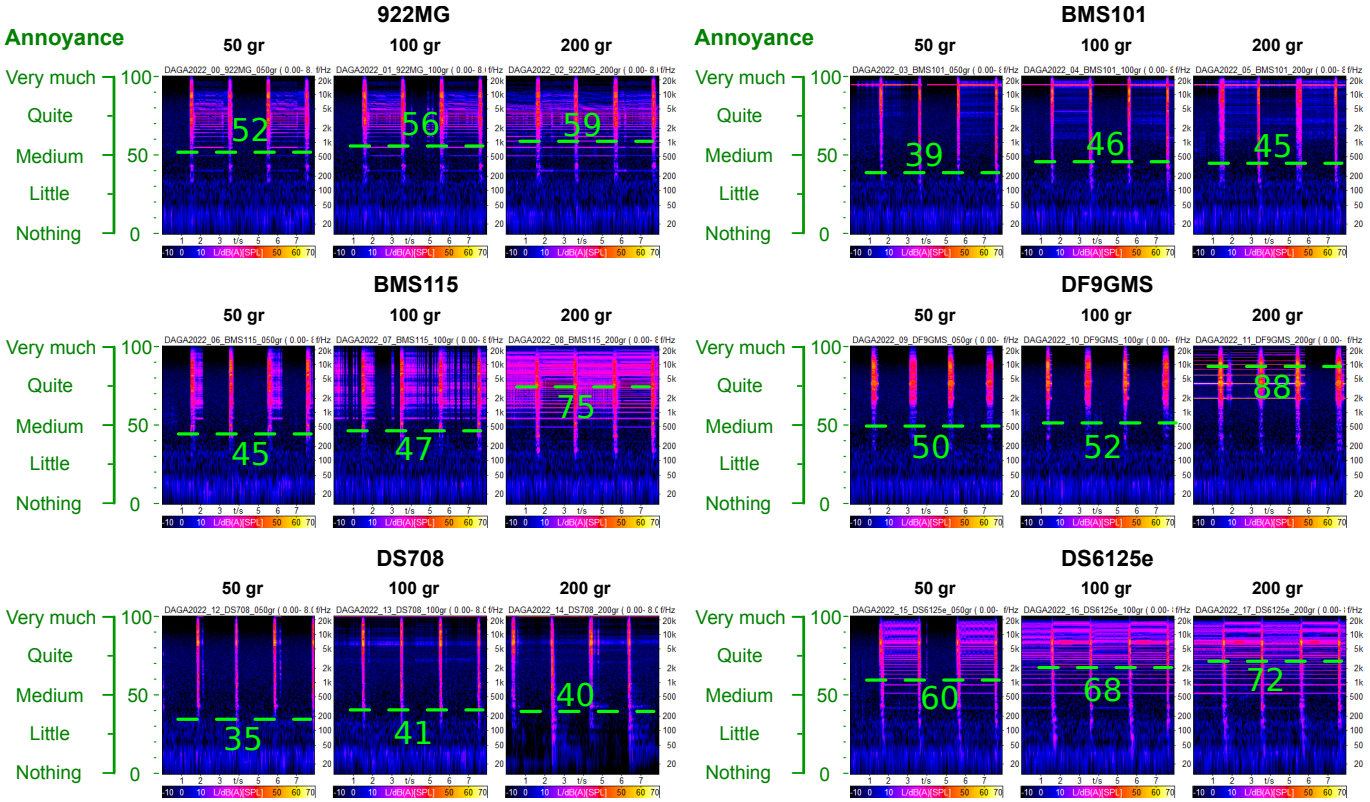

Figure 4: Spectrograms of the A-weighted sound pressure level over time for each servomotor under three load conditions: 50, 100 and 200 grams.The mean annoyance values are displayed in green over their corresponding graphs.

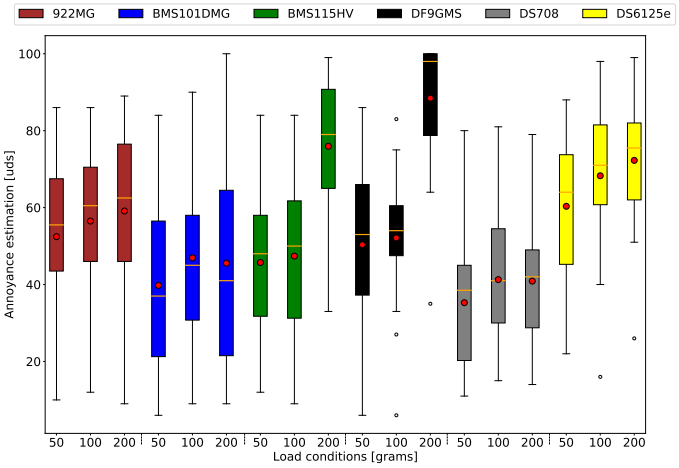

Figure 5: Annoyance ratings of the perception test, using for each stimulus the mean value of each subject. The overall mean values are displayed as red dots, while median values are represented as orange horizontal lines.

In every case the motion, which consists of 4 successive rotations and therefore an increase of the SPL, may be visualized. However, there are variations between actuators. One key difference between the motors with medium and high annoyance ratings, such as the 922MG and the DS6125e, and the motors with low annoyance ratings, such as the BMS101 and the DS708, is the presence of continuous noise between motions, composed by high frequency components. As seen in the graphs, conditions where the mean annoyance perception is higher include high frequency components between motions. For example, the DS708, which doesn't generate this constant noise, presents overall mean annoyance ratings equal or lower to 41. On the other hand, the DS6125e, that experiences this issue, generates higher annoyance on the subjects, which overall mean values of 60, 68 and 72 for 50, 10 and 200 grams. Such influence on annoyance is noticeable in the BMS115HV too, with low to medium ratings for 50 and 100 grams, where there are no continuous components, but for 200 grams both the constant high frequency components and the annoyance perception ratings increase. However, it's relevant to mention that the stimulus that reported the highest annoyance was the DF9GMS for 200 grams, where there are only a few tonal components present between motions, instead of multiple frequencies.

Annoyance perception results presented high variability amongst test subjects, as shown in Fig. 5, where for each stimulus the mean of the three values of each test subject is used. From a first glance, it seems like increasing the load would increase the annoyance. In order to corroborate that assumption, a repeated measures ANOVA for each motor is made, obtaining the p-values shown in table 2. These are all lower than 0.05, indicating that the null hypothesis, which assumes that all cases have the same mean, is rejected, even for the actuators with least annoyance variation such as the BMS101 and the DS708.

Table 2: P-values for repeated measures ANOVA test in each motor condition, analysing the influence of the load on the annoyance perception.

Motor	P-value
DF9GMS	0.016072
BMS101	0.021204
BMS115	2.515e-10
DF9GMS	3.9689e-13
DS708	0.02178
DS6125e	3.6471e-05

Discussion

In this work the sound of various servomotors, operating in similar working conditions, was recorded, and their sounds used in a perception test with various subjects, where their respective annoyance was rated and subsequently analysed. According to such results, the BMS101 and DS708 servomotors offered the lowest annoyance values for various load conditions, followed by the BMS115HV, that presented also low to medium annoyance for 50 and 100 grams. On the other hand, the influence of continuous high frequency and tonal components on annoyance perception has been noted, and would require further analysis, as there may be various causes for their generation.

One possible source would be the torque limits of the actuators, as the needed force to move the loads may be too high. Another possible reason is related with the control system. With regard to their structure, servomotors commonly consist of a DC motor, a gear reduction system, and the built-in electronics, that usually include a position sensor, alongside a closed loop control system, where the desired position is received from an external controller, and then compared with the measured one, powering the motor accordingly. Usually under no load conditions the control system operates at its best, first reaching the target position and then stopping the powering of the actuator. However, under load conditions, it's more probable to have a position error, which may cause the control system to keep powering the actuator, which may turn into noise. This seems like one of the most probable causes for the continuous sounds between motions. One relevant detail in this regard is the algorithm used in the DF9GMS, as this servomotor was the only one that had a built-in speed control system, instead of a position one. Therefore, the position control was implemented externally through software, which may in turn have influenced the motor performance, and thus the ratings, having such actuator for 200 grams the highest annoyance of all. Therefore, improvements regarding motor control may prove useful for reducing high frequency and tonal components.

With regard to haptics, various changes may be applied to the setup, in order to create higher similarity with real working conditions, thus more immersive experiments. It may include modifications to multiple aspects, ranging from the measurement setup to the annoyance experiment itself. With regard to the first, a higher distance could be chosen, as 20 cm between the actuator and the microphone may be too low. Regarding motor actuation, it could be interesting to analyze different types of stimuli, such as variable forces. Additionally, with regard to haptic immersion, it would be advisable to modify the annoyance experiment in order to incorporate the visual and haptic senses, as in this work the test subjects only listened to the sounds, without any further stimuli. One last detail to take into account in future studies would be to analyse these sounds with regard to its psychoacoustic parameters, as here only the A-weighted SPL was considered.

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