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Optimization of the power targeted to the frequency region of maximum tactile sensitivity

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Abstract

Tactile stimulation is a means of transferring information to visually handicapped individuals. A study of the power delivered by the driving waveform to a transducer used for tactile stimulation as a function of the parameters of the waveform is presented. The power delivered within the region of maximum tactile skin sensitivity, Q_{fw}, is compared to the total power delivered by the waveform in one cycle, P_T, as a function of the waveform parameters with the objective of finding the parameters that would maximize the ratio Q_{fw}/P_T. In this study, the driving waveform is composed of an excitatory period followed by a recovery time. The excitatory period is formed by a burst of rectangular pulses modulated in amplitude by different waveforms. After a Fourier decomposition of the excitatory waveform, the contribution of each harmonic was added to compute the power delivered within the frequency region of interest. Additionally, to take in account the contribution of each harmonic in the overall tactile sensation, the power delivered within the region of maximum tactile skin sensitivity was weighed by the skin tactile sensitivity function and then linearly summed. The results show that the ratio Q_{fw}/P_T has a maximum for pulse widths between 0.8 and 1.2 ms for all pulse frequencies in the range 50–700 Hz when the tactile sensitivity function was not considered. The optimum pulse width, when the tactile sensitivity weighing function is considered in the computations, was in the range between 0.7 and 1.7 ms for pulse frequencies between 50–700 Hz. The ratio Q_{fw}/P_T is invariant to changes in the number of pulses per burst and the length of the recovery time. Once the tactile system frequency response is identified, all the waveform parameters can be specified for maximum power targeted to the region of maximum tactile sensitivity.

Introduction

The possibility of transferring information through tactile stimulation to aid visually handicapped individuals was demonstrated more than two decades ago [1–4]. Since the first prototype, different types of tactile displays and modes of stimulation have been implemented [5–7]. The bulk, weight, inefficiency and high cost of the hardware involved remain an obstacle to build a device that could be easily manipulated by the blind community [8, 9]. In the past few years, much progress has been made in VLSI and CCD technology that would allow construction of a usable prototype. Furthermore, through an appropriate specification of the parameters of the excitatory waveform matching them to the tactile system characteristics, it is possible to reduce the requirements of power and hardware components of the system [10–12]. Several studies have been presented partially achieving this goal in vibrotactile stimulation [11–16], and also in electrotactile stimulation [17–19].

The effect of using an excitatory waveform, composed of a burst of short duty cycle rectangular pulses followed by a recovery time, was studied previously [13–15]. It was investigated the effect of changing the duty cycle of the excitatory waveform for a set of conditions: very short pulse width (≤ 0.25 ms), fixed pulse frequency at 250 Hz, and a rectangular window modulating the burst of pulses [13]. It was shown that by using short duty cycle rectangular pulses, the power delivered by the system could be reduced [13–15]. Employing the same excitatory waveform, it was found experimentally, for a number of pulse frequencies (in the range 25 to 800 Hz), a corresponding pulse width (in the range 0.2 to 39.9 ms) which maximizes sensitivity and minimizes the power delivered by the waveform [15]. The cited studies involved an incomplete range of parameters and considered only a rectangular envelope modulating the burst of pulses.

In this study, the driving waveform is composed of an excitatory period followed by a recovery time. The latter to avoid adaptation of the tactile system to the stimulation [13]. The excitatory period is formed by a burst of rectangular pulses that can be modulated in amplitude by any chosen waveform. The significant parameters of the excitatory waveform are: modulation waveform, *MW*, pulse width, *W*, pulse frequency, *F*, number of pulses per burst, *NPB*, and recovery time *RT*. Figure 1 shows the driving waveform to the transducer. The parameters were varied in the following ranges: *F* from 10 to 1000 Hz with steps of 1 Hz and *W* from 1 μs to (1/F) with a step of 0.1 ms. The parameters, *NPB* and *RT*, were fixed at values of 10 and 0.5 s respectively [13] because they do not affect significantly the frequency distribution of the waveform. This excitatory waveform is preferred over continuous type waveforms because the off-periods between pulses permit multiplexation of several signals into one physical channel for hardware reduction. Besides, the implementation of the hardware to generate short rectangular pulses is simpler compared to more complex waveforms. In this study, we investigated the relevant parameters of the driving waveform to target most of the power delivered by the waveform to the region of maximum tactile sensitivity while minimizing the power delivered out of this region.

Methods

The power delivered by the waveform was studied as a function of the waveform parameters using a Fourier decomposition of the excitatory waveform. The power delivered within the region of maximum tactile sensitivity was computed adding the contribution of each harmonic within the frequency region of interest and then was compared to the total power delivered per cycle. Additionally, to take in account the filtering characteristics of the tactile system, each of the frequency components of the waveform was weighed by the tactile sensitivity function [20] and then linearly summed.

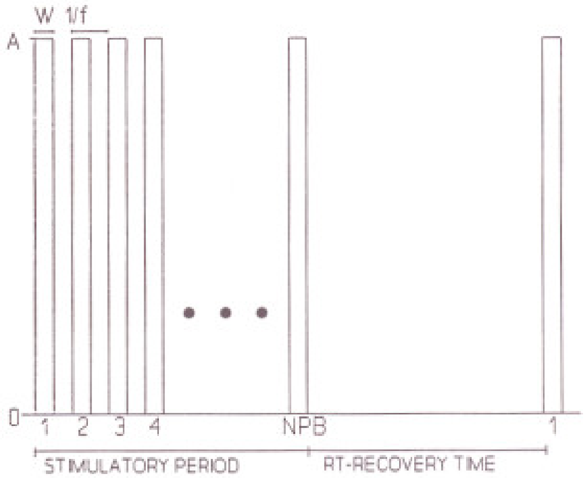

Fig. 1. Driving waveform to the transducer as a function of time. The waveform is composed of a burst of *NPB* short duty cycle rectangular pulses of amplitude *A* followed by a recovery time. The modulation waveform to the burst of pulses is rectangular with pulse frequency, *F*, and pulse width, *W*.

To find the optimum envelope for the burst of pulses, a computer search was implemented to maximize the ratio between the power delivered within the region of maximum tactile sensitivity and the total power. This ratio was computed for all possible combinations of pulse amplitudes for the 10 pulses in steps of 0.1 in a range (0.1, 1).

Waveform analysis

While transferring information from a static picture through tactile stimulation, the waveform excites the transducer in a repetitive manner, therefore, the waveform can be assumed to be periodic. Given an excitatory waveform *S(T)* and the Fourier Series coefficients S_n, the Fourier transform of the periodic waveform is given by:

$$F(\omega) = 2\pi\Sigma_n S_n \delta(\omega - n\omega_o) \qquad (1)$$

For the driving waveform of Fig. 1, $\omega_o = 2\pi/T$, with $T = TS + RT$. $TS = (NPB\text{-}1)/F + W$ and *RT* is the recovery time. Computation of the power delivered by the excitatory waveform is based on the Fourier coefficients. The power delivered by the waveform within the frequency range between harmonics n1 and n2 is given by

$$Q_{fw} = 2\sum_{n_1}^{n_2} | S_n |^2 \tag{2}$$

The total power per cycle can be computed as:

$$\mathrm{P}_T = \frac{1}{T}\int_o^T S^2(t)\,dt \tag{3}$$

Approximation

For the driving waveform studied here, a general expression can be obtained when the pulses have constant amplitude during the inverval *W* (pulse width), i.e., the pulse does not follow the envelope during *W*. This approximation allows a simpler hardware implementation of the wave-generator, and as it will be shown, the results do not differ significantly from the case where the pulse follows the envelope during *W*. If we consider *NPB* pulses of width *W* and pulse amplitudes A_k, where $k = 0, \ldots, NPB$, and A_k are samples of the waveform modulating the burst of pulses, the Fourier coefficients are:

$$S_n = \frac{1}{T}\sum_{k=0}^{NPB-1}\int_{\frac{k}{F}}^{\frac{k}{F}+W} A_k e^{-jn\omega_o t}dt \tag{4}$$

$$S_n = \frac{1}{T}\sum_{k=0}^{NPB-1}\frac{A_k}{-jn\omega_o}e^{-jn\omega_o\frac{k}{F}}(e^{-jn\omega_o W}-1) \tag{5}$$

$$S_n = \frac{W}{T}sinc(n\omega_o\frac{W}{2})e^{-jn\omega_o\frac{W}{2}}(\sum_{k=0}^{NPB-1}A_k e^{-jn\omega_0\frac{k}{F}}) \tag{6}$$

The power delivered by the waveform within the frequency range between harmonics n1 and n2 is computed from (6) according to (2). From (3), the total power per cycle delivered by the waveform envelope is

$$P_T = \frac{W}{T}(\sum_{k=0}^{NPB-1}A_k^2) \tag{7}$$

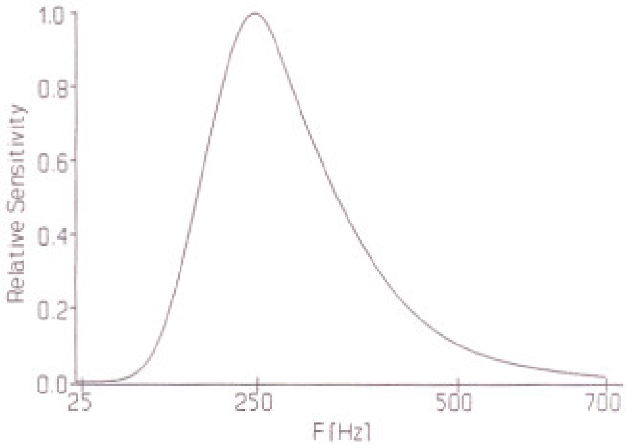

Fig. 2. Normalized sensitivity weighing function as a function of frequency.

Tactile sensitivity weighing function

In order to consider the filtering characteristics of the tactile system, the frequency response of the tactile system was included. Each frequency component of the excitatory waveform was weighed by the human tactile threshold sensitivity function [20]. Sample points from the human tactile threshold frequency response were taken from [20] and interpolated using a cubic spline method. The results of the interpolation were converted to linear scale, inverted and normalized to produce the sensitivity weighing function with a maximum value of 1 at 250 Hz. Therefore, other frequencies will have weighing values ≤ 1. Figure 2 shows the normalized sensitivity weighing function, H_f, as a function of frequency. The contributions of each harmonic of the excitatory waveform to the power delivered within a specific frequency range (*nmin, nmax*) can be weighed by the corresponding relative amplitude of the normalized tactile sensitivity weighing function.

$$Q_{fw} = 2\sum_{n=nmin}^{nmax}|F(n\omega_0)H_f(n\omega_o)|^2 \tag{8}$$

Optimum envelope

The spectrum of the excitatory waveform can be altered by changing the envelope modulating the burst of pulses. Therefore, it is possible to determine the envelope that will maximize the ratio between the power delivered within the region of maximum tactile skin sensitivity, Q_{fw}, and the total power delivered by the

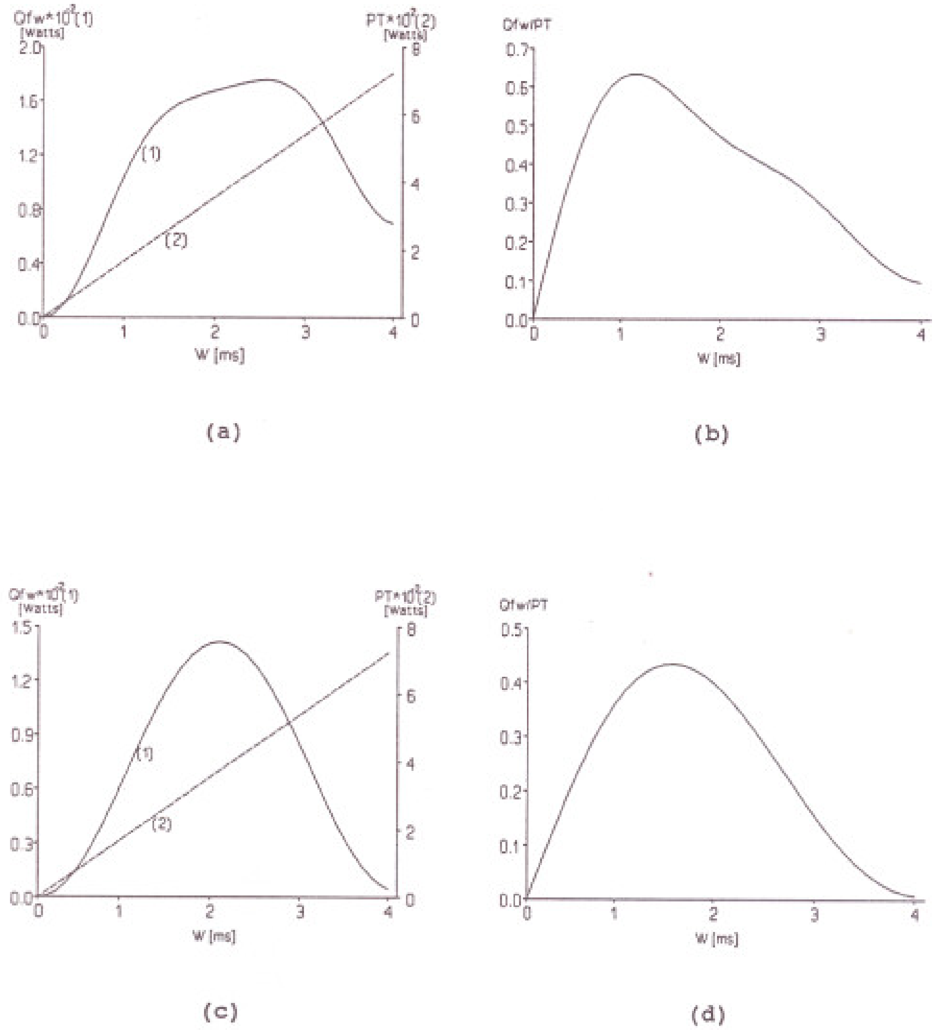

Fig. 3. (a.1) Power, Q_{fw}, delivered by the excitatory waveform within the frequency range 25–700 Hz and (a.2) total power, P_T, as a function of pulse width without sensitivity weighing function. (b) Ratio between Q_{fw} and P_T without sensitivity weighing function. (c.1) Power, Q_{fw}, delivered by the excitatory waveform within the frequency range 25–700 Hz and (c.2) total power, P_T, as a function of pulse width with sensitivity weighing function. (d) Ratio between Q_{fw} and P_T with sensitivity weighing function. (a), (b), (c) and (d) for pulse frequency of 250 Hz, NPB = 10 and RT = 0.5 s.

waveform in one cycle, P_T. For the discussion of results it was considered that a burst of pulses with uniform amplitude corresponds to the case of a rectangular envelope of amplitude 1.

Besides employing envelopes such as sinusoidal and gaussian, a search was implemented in a computer to maximize the ratio Q_{fw}/P_T for all possible combinations of pulse amplitudes in steps of 0.1 from 0 to 1. This procedure was implemented modifying only the pulse amplitudes, A_k, and all other parameters such as pulse frequency, pulse width, NPB and RT were kept constant. Pulse amplitudes that would maximize the ratio Q_{fw}/P_T were selected for both cases with and without the human tactile sensitivity function.

Results

Optimum pulse width and pulse frequency

The power delivered by the waveform within the range of frequencies 25–700 Hz was computed as a function of pulse width for the rectangular envelope using equation (6) for a fixed pulse frequency of 250 Hz, NPB =

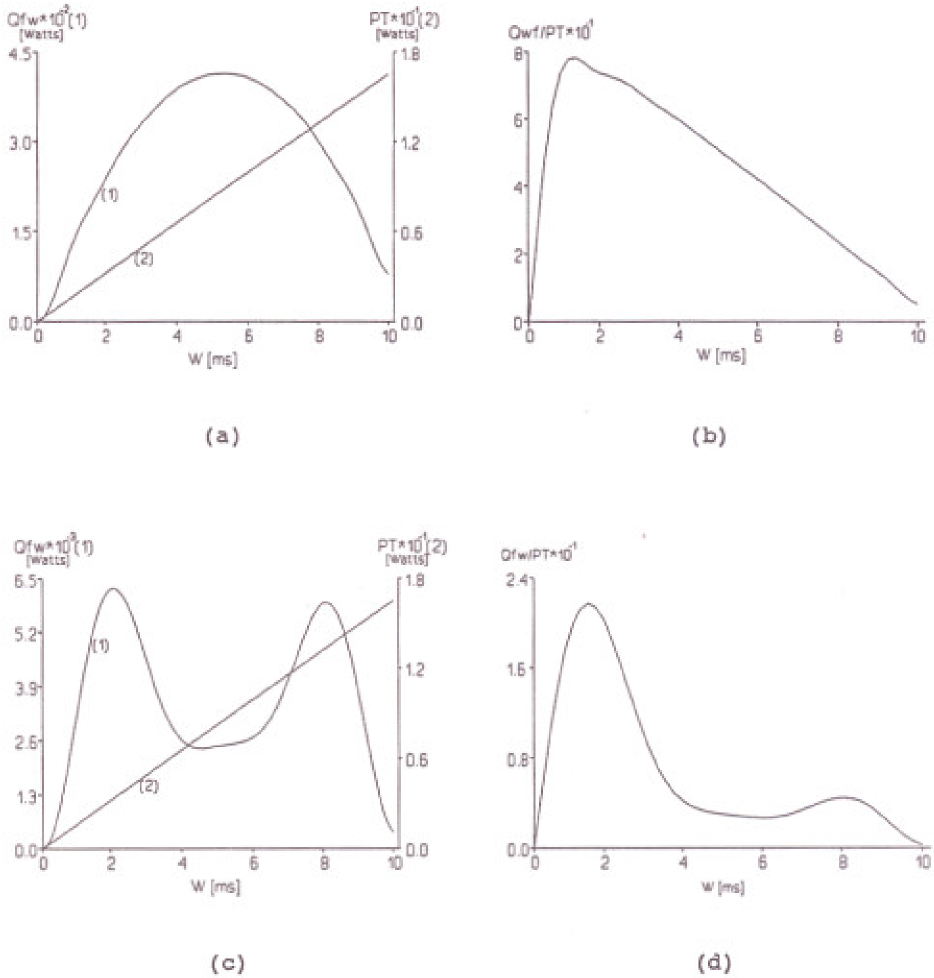

Fig. 4. (a.1) Power, Q_{fw}, delivered by the excitatory waveform within the frequency range 25–700 Hz and (a.2) total power, P_T, as a function of pulse width without sensitivity weighing function. (b) Ratio between Q_{fw} and P_T without sensitivity weighing function. (c.1) Power, Q_{fw}, delivered by the excitatory waveform within the frequency range 25–700 Hz and (c.2) total power, P_T, as a function of pulse width with sensitivity weighing function. (d) Ratio between Q_{fw} and P_T with sensitivity weighing function. (a), (b), (c) and (d) for pulse frequency of 100 Hz, $NPB = 10$ and $RT = 0.5$ s.

10 and RT = 0.5 s. The results are shown in Fig. 3.a.1. The total power delivered by the waveform as a function of pulse width was calculated according to (7) and the results are shown in Fig. 3.a.2. Figure 3b shows the ratio between the power delivered within the range of frequencies 25–700 and the total power delivered by the waveform as a function of pulse width for a pulse frequency of 250 Hz, NPB = 10, and RT = 0.5 s. The same results are shown in Fig. 4a and 4b for a pulse frequency of 100 Hz.

The same computation was performed weighing the spectral components of the excitatory waveform by the tactile sensitivity weighing function (Fig. 2). Results for the power delivered within the range of frequencies 25–700 considering the tactile sensitivity weighing function are shown in Fig. 3.c.1 for a fixed pulse frequency of 250 Hz, NPB = 10 and RT = 0.5 s. The total power delivered by the waveform as a function of pulse width is shown in Fig. 3.c.2. Figure 3d shows the ratio between the power delivered within the frequency region 25–700 Hz weighed by the tactile sensitivity weighing function and the total power delivered by the waveform. The same results are shown in Fig. 4c and 4d for a pulse frequency of 100 Hz.

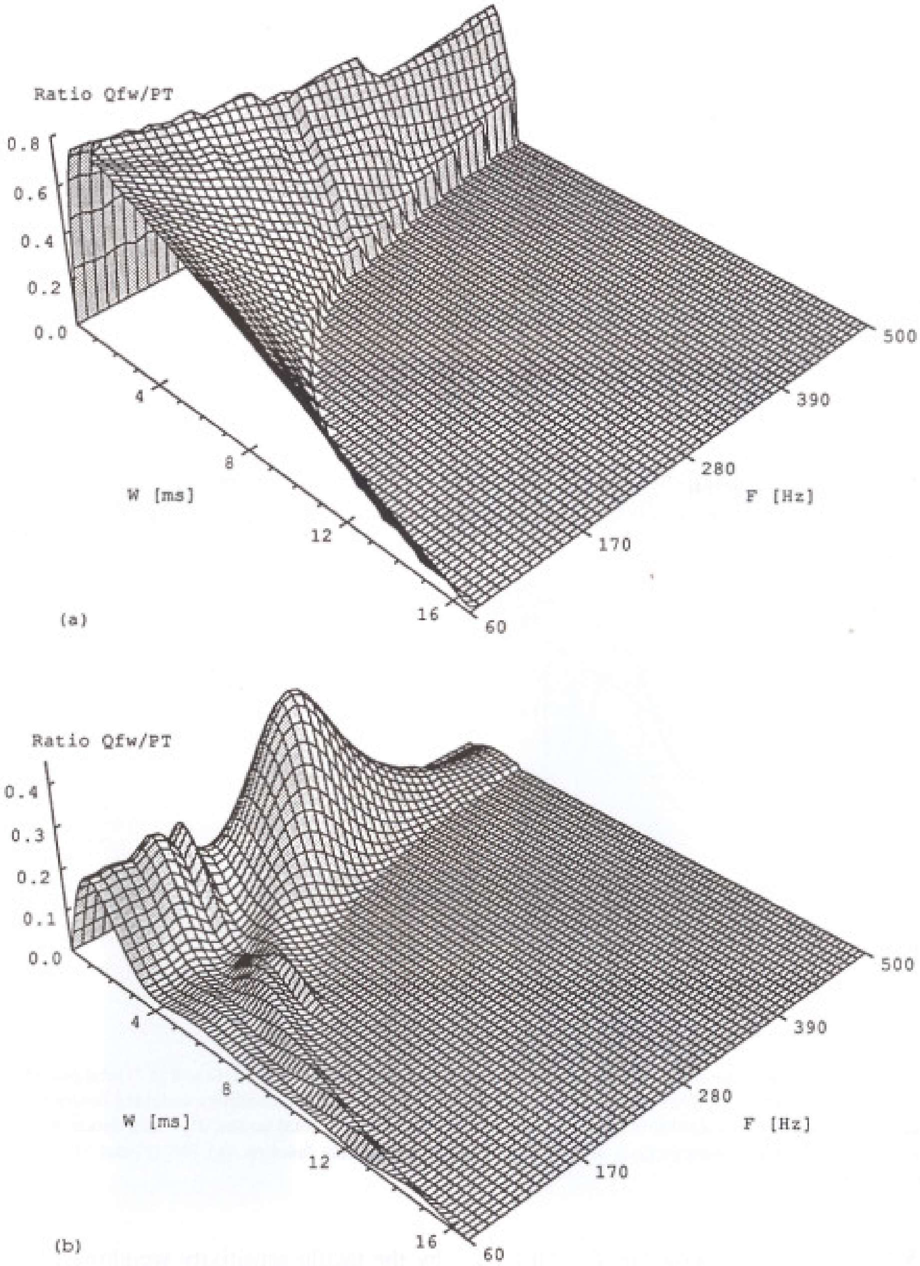

Fig. 5. Ratio, Q_{fw}/P_T, power delivered within the frequency region of máximum tactile sensitivity to the total power delivered by the excitatory waveform as a function of pulse width, *W*, and pulse frequency, *F*. (a) without tactile sensitivity weighing function and (b) with tactile sensitivity weighing function.

Figure 5 shows two 3-D plots of the ratio, Q_{fw}/P_T, as a function of pulse width (in the range 0–1/F) and pulse frequency (in the range 60–500 Hz). Figure 5a shows the results without considering the tactile sensitivity weighing function and Fig. 5b shows the results weighing the spectral components by the tactile sensitivity weighing function. These results show that the ratio, Q_{fw}/P_T, has a maximum as a function of pulse width. The maximum is located at pulse frequencies between 0.8 and 1.2 ms for the case with no tactile sensitivity weighing function and between 0.7 and 1.7 for the case with the tactile sensitivity weighing function. The ratio is invariant to changes of *NPB* and *RT*.

For example the present study enables, for a pulse frequency of 100 Hz, to select an optimum pulse width of 1.1 ms that reduces the total power delivered by the waveform to 62.7% of the total power delivered by a 50% duty cycle (5 ms) waveform, while maintaining the same power within the region of frequencies of maximum tactile sensitivity.

Constant vs. continuous amplitude pulses

Comparing results from the computation of the ratio, Q_{fw}/P_T, for pulses following the envelope within *W*, and those of pulses with constant amplitude A_k during *W*, yield differences that have some significance for large pulse widths only. As an example, Fig. 6a shows the ratio Q_{fw}/P_T for a sinusoidal envelope as a function of pulse width for a pulse frequency of 250 Hz (*NPB* = 10 and *RT* = 0.5 s) and no tactile sensitivity weighing function. Figure 6b shows the same ratio considering the tactile sensitivity weighing function. Figures 6c and 6d show the ratio Q_{fw}/P_T for a gaussian envelope as a function of pulse width for a pulse frequency of 250 Hz (*NPB* = 10 and *RT* = 0.5 s) for the cases with and without tactile sensitivity weighing function, respectively. The results show no significant difference at pulse widths where the ratio is maximum. Therefore, it can be concluded that there is no drawback in using a constant pulse during *W*, on the contrary, the hardware implementation is simpler.

Optimum envelope

A computer search was implemented with the purpose of finding an optimum envelope for the burst of pulses to maximize the ratio Q_{fw}/P_T, for all possible combinations of pulse amplitudes, A_k, in steps of 0.1 for a fixed combination of *F*, *W* (optimum), *NPB* = 10 and *RT* = 0.5 s.

As expected, it was found that envelopes presenting a spectrum with components following the shape of the weighing function for the frequency region of maximum tactile sensitivity, and with fewer components out of this region, resulted in higher values for the ratio of Q_{fw}/P_T.

Case without tactile sensitivity weighing function

All frequency components were added within the region of tactile sensitivity with no amplitude modification. The envelope for the train of pulses maximizing the ratio Q_{fw}/P_T resulted null in most part of the excitatory period eliminating most of the pulses. Therefore, the envelope optimizing the ratio Q_{fw}/P_T originated a repetition rate of 26 Hz. At a pulse frequency of 26 Hz the maximum for the ratio Q_{fw}/P_T resulted at a pulse width of 2.5 ms. This pulse frequency is the lowest end of the region of tactile sensitivity considered in this study. For a combination of parameters *F* = 26 Hz, *W* = 2.5 ms, *NPB* = 10, *RT* = 0.5 and *A* = 1.0, only 72.32% of the total power delivered by the waveform at *F* = 250 Hz (with optimum parameters of *W* = 1.0 ms, *NPB* = 10, *RT* = 0.5) is required to produce the same amount of power within the region of maximum tactile sensitivity. As another example, the waveform with parameters *F* = 26 Hz, *W* = 2.5 ms, *NPB* = 10, *RT* = 0.5 and *A* = 1.0 requires only 89.69% of the power delivered by a *F* = 100 Hz (with optimum parameters of *W* = 1.1 ms, *NPB* = 10, *RT* = 0.5) to produce the same amount of power within the region of maximum tactile sensitivity.

Case with tactile sensitivity weighing function

The spectral components of the excitatory waveform were weighed by the tactile sensitivity weighing function. The optimum envelope maximizing the ratio, Q_{fw}/P_T, resulted for *F* = 250 Hz, *W* = 1.5 ms and with amplitude distribution for the 10 pulses given by: 0.24375, 0.43125, 0.58125, 0.68750, 0.74375, 0.74375, 0.68750, 0.58125, 0.43125, 0.24375. By choosing the waveform with optimum envelope, *F* = 250 Hz and *W* = 1.5 ms, only 48.51% of the total power delivered by a waveform with rectangular envelope, *F* = 100 Hz and *W* = 1.4 ms, is necessary to produce the same amount of power within the region of maximum tactile sensitivity. The pulse width, *W* = 1.4 ms, is the pulse width maximizing the ratio, Q_{fw}/P_T, for the waveform with *F* = 100 Hz. For the waveform with optimum envelope, *F* = 250 Hz and *W* = 1.5 ms, the total power required to produce the same power within the region of maximum tactile sensitivity is 96.97% of that required by a waveform with same parameters but rectangular envelope. This case corresponds to the worst improvement that can be obtained when choosing the waveform, *F* = 250 Hz and *W* = 1.5 ms with optimum envelope, for comparison with other waveforms with rectangular envelopes.

By choosing the waveform, *F* = 250 Hz, *W* = 1.5 ms and optimum envelope, instead of a waveform of the same pulse frequency, rectangular envelope and 50%

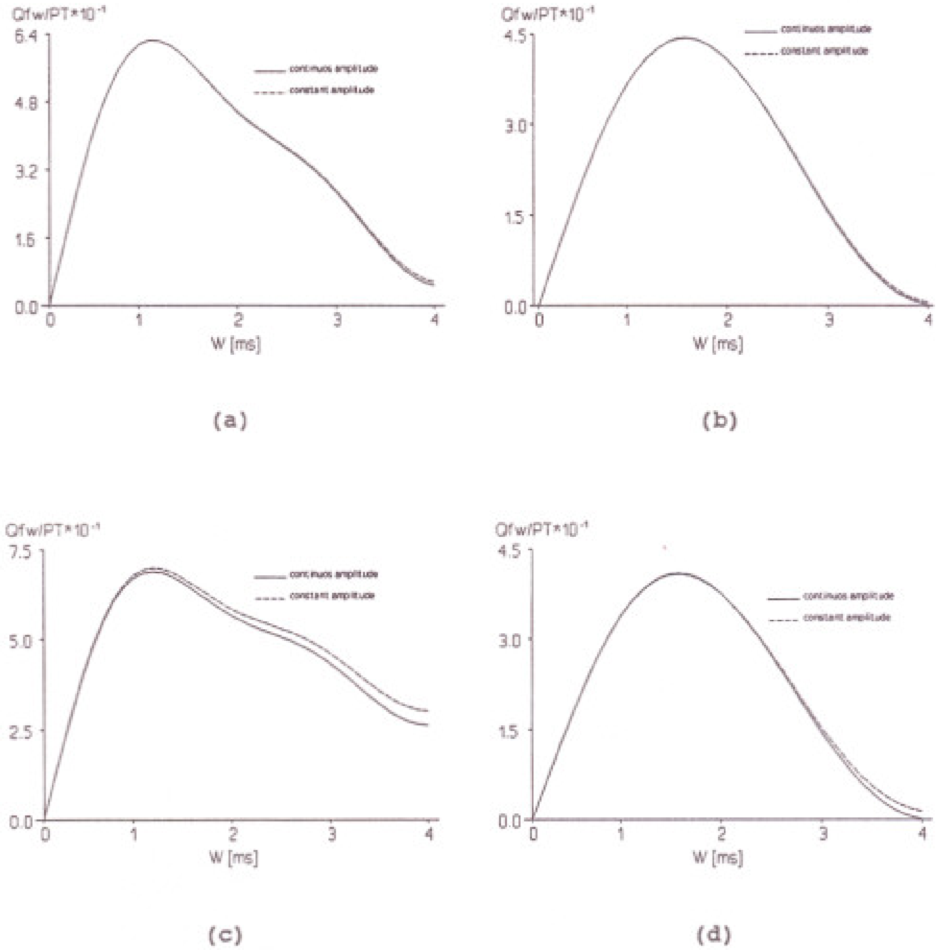

Fig. 6. Comparison of results for the ratio Q_{fw}/P_T for pulses with constant amplitude within W and pulses following the envelope during W. The ratio Q_{fw}/P_T is shown for a sinusoidal envelope as a function of pulse width for $F = 250$ Hz, $NPB = 10$, $RT = 0.5$ s and (a) no tactile sensitivity weighing function, and (b) with tactile sensitivity weighing function. The same ratio Q_{fw}/P_T is shown for a gaussian envelope with (c) no tactile sensitivity weighing function, and (d) with tactile sensitivity weighing function.

duty cycle, the total power required to maintain the same amount of power within the region of maximum tactile sensitivity can be reduced to 85%. The rectangular envelope and 50% duty cycle correspond to the case where there is no optimization for the envelope nor in the pulse width of the waveform.

For a combination of parameters, $F = 250$ Hz, $W = 1.5$ ms and optimum envelope, it is necessary only 50.31% of the total power required by a waveform with $F = 26$ Hz, $W = 1.4$ ms and rectangular envelope, to maintain the same power within the region of maximum tactile sensitivity. The 1.4 ms is the optimum pulse width obtained for the waveform, $F = 26$ Hz, with the tactile sensitivity weighing function.

Conclusions

The results show that for a chosen envelope the power delivered within the frequency range 25–700 Hz, where the tactile system is most sensitive to stimulation, increases with pulse width until pulse widths around $W = 1/(2F)$ and then decreases again. The total power delivered by the waveform increases linearly as a function of pulse width.

The authors show that the ratio between the power delivered in the frequency region of maximum tactile sensitivity, Q_{fw}, and the total power delivered by the waveform, P_T, has one maximum as a function of pulse width. This optimum permits choosing a pulse width for each possible pulse frequency where most of the power delivered by the waveform is targeted to the region of maximum sensitivity of the tactile system. The ratio Q_{fw}/P_T has a maximum, as a function of pulse width, around 1.1 ms for any pulse frequency when the tactile sensitivity weighing function is not considered.

The study enables to choose the parameters of the excitatory waveform to reduce the total power delivered while maintaining the same amount of power within the region of maximum tactile sensitivity. By making a suitable selection of the parameters of the excitatory waveform, e.g., $F = 250$ Hz and $W = 1.0$ ms, the total power delivered by the waveform can be reduced to 71.75% of the power delivered by the same waveform but 50% duty cycle (2 ms), while maintaining the same amount of power within the region of maximum tactile sensitivity. As another example, the study enables, for a pulse frequency of 100 Hz, to select an optimum pulse width (1.1 ms) that reduces the total power delivered by the waveform to 62.7% of the total power delivered by a 50% duty cycle (5 ms) waveform, while maintaining the same power within the region of frequencies of maximum tactile sensitivity. For the same pulse frequency of 100 Hz, if the tactile sensitivity weighing function is considered, the selection of the optimum pulse width (1.4 ms) to deliver the same amount of power to the frequency region 25–700 Hz, requires only 13.54% of the total power delivered by a 50% duty cycle (5 ms) waveform.

This study did not included the frequency response of the transducer itself because that depends on the particular device being used. Nevertheless, by including the appropriate frequency response of the chosen transducer, corrections to the calculations can be easily implemented.

While maximizing the ratio Q_{fw}/P_T, it was possible to determine an optimum combination of pulse frequency, pulse width and envelope for the waveform for both cases with and without tactile sensitivity weighing function.

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