envelopes is the composite effect that is commanded to the haptic transducer. The weighting factors for both the low and high passed signals are determined by the frequency of the effect and its magnitude. The combined modulated effect is arrived at by multiplying the high pass weighted signal by the modulating envelope. The process is first described herein in terms of providing a high-strength low frequency tactile sensation, i.e., there is a single low frequency effect (waveform) that is desired to be output, and a high frequency waveform is created to combine with the commanded low frequency waveform to create a high strength sensation.

[**0095**] One problem, similar to the one mentioned above, is that the calculated effect might exceed the full scale output of the actuator assembly. That is, the amplifier can be commanded to 100%, and the output effect may be clipped, resulting in amplifier saturation and effect distortion, as discussed with respect to **FIG. 7**. To eliminate this problem, the process of the present invention can normalize the waveforms so that the maximum commanded output from the filter is the scaled sum of the magnitudes of the component effects such that the maximum commanded output will never exceed 100% and will never have to be clipped. In some embodiments, a certain amount of saturation and distortion is acceptable in a product, and the normalized output can be slightly clipped, e.g., 20% of the output signal can be clipped. In either the pure normalized or marginally saaturated case, the saturation and distortion is controlled to create a more consistent feel across different software applications. The overdrive or saturation factor can also be a value that is selectable by the user, e.g., with the value **1** providing the highest fidelity, and higher values providing higher average force output at the cost of distortion.

[**0096**] **FIG. 8** is a graph **300** illustrating the low pass and high pass filters of the present invention. The curve **302** represents the high pass filter, which lowers the gain of the source waveform at lower frequencies. The high pass filter is expressed by the function:

$$\alpha=1-1/(1+f/f_c) \quad (1)$$

[**0097**] where α is the high pass gain, and f_c is the filter corner frequency, which is the threshold frequency as explained above.

[**0098**] Curve **304** represents the low pass filter, which lowers the gain of the source waveform at higher frequencies. The low pass filter is expressed by the function:

$$\beta=1/(1+f/f_c) \quad (2)$$

[**0099**] where β is the low pass gain and fc is the threshold frequency.

[**0100**] **FIG. 9** is a graph **320** illustrating two source waveforms which will be used in the present example explanation. Waveform **322** has the commanded (desired) low frequency, while waveform **324** has a higher frequency above the threshold frequency. In the example shown, waveform **322** is 1 Hz, and waveform **324** is 30 Hz. Waveform **324** can be of an arbitrarily chosen high frequency, or can be chosen to have a particular high frequency that is efficiently output by the actuator assembly. Waveforms **322** and **324** are shown normalized to a magnitude of 1. Although the waveforms are shown as sinusoids in the example, other types of waveforms can also be used, such as square waves, triangle waves, sawtooth-shaped waves, etc.

[**0101**] The low pass filter process takes each of the two effects and calculates a low pass gain β for each effect that contributes to the modulation envelope. **FIG. 10** is a graph **330** showing a waveform **332** that is the envelope function generated from the 1 Hz function. The amplitude is close to 1 since β is almost unity for signals much less than the 10 Hz low pass corner frequency and the amplitude M of the source signal equals 1. Since this is the only other effect besides the high frequency waveform **324**, and the high frequency waveform does not have a significant low pass component, waveform **332** dominates the main envelope function for the high frequency waveform.

[**0102**] The envelope for the nth effect can be expressed by:

$$|\Sigma_{i,i}\beta_i M_i \sin(\omega_i t+\phi_i)| \quad (3)$$

[**0103**] where i indicates the i^{th} waveform, M is the magnitude, ω is the frequency, and Φ is the phase of the low frequency signal. The envelope is the sum of all the low-passed signals $\beta_{i\ i}M_i \sin(\omega_i t+\phi_i)$, where in this case i=1 for the low frequency signal and i=2 for the high frequency signal. For the high frequency signal, n=2 and its envelope function is $|\Sigma_{i,i}\beta_i M_i \sin(\omega_i t+\phi_i)|=|\beta_1 M_1 \sin(\omega_1 t+\phi_1)|$.

[**0104**] To calculate the transformed effect f_i (t), the high passed signal is multiplied by the modulation envelope expressed by equation (3). This can be expressed by:

$$f_i(t)+\alpha_i M_i \sin(\omega_i t+\phi_i)[|\Sigma_{j,j}\beta_i \sin(\omega_i t+\phi_i)|] \quad (4)$$

[**0105**] where $\alpha_i M_i \sin(\omega_i t+\phi_i)$ is the signal that has been filtered by the high pass filter and $|\Sigma_{j,j}\beta_i \sin(\omega_j t+\phi_j)|$ is the modulation envelope, and where j indicates another count of waveforms (here, e.g., j=1 can be the low frequency waveform, and j=2 can be the high frequency waveform). When i=1 (low frequency signal), the first term having the α_1 gain term is small, and β_2 is also small so that f_1 (t) is very small. When i is 2 (high frequency signal), the first term is large, and the second product term (modulation envelope) is large (because with j=1, $\beta_{1=}$ is large), creating an f_2 (t) that is substantially larger than f_1 (t).

[**0106**] Each of the product contributions f_i (t) for each of the effects are added together, as expressed below:

$$f_{composite}(t)=\Sigma_i f_i(t) \quad (5)$$

[**0107**] **FIG. 11** is a graph **340** showing a waveform **342** that is the non-normalized sum of the products using the two waveforms **322** and **324** in the equations shown above. The waveform **342** shows the output waveform produced by the sum of products method. The high frequency waveform (30 Hz) content is represented by the high frequency sinusoid and the low frequency (1 Hz) sinusoid is represented as the modulation envelope. Since the low frequency sinusoid is below the chosen filter corner frequency of 10 Hz, it comprises almost all of the envelope, or amplitude contour of the waveform. Since the high frequency signal is well above the corner frequency, it constitutes almost all of the high passed signal content.

[**0108**] The sum of products filtering method described above causes the actuator assembly of **FIG. 3** to operate closer to the center of its range of motion than the addition method described above with respect to **FIG. 7**. Thus, the inertial mass does not become centered as close to an end to its travel as in the addition method, allowing fuller-strength tactile sensations to be output for any combined waveforms.