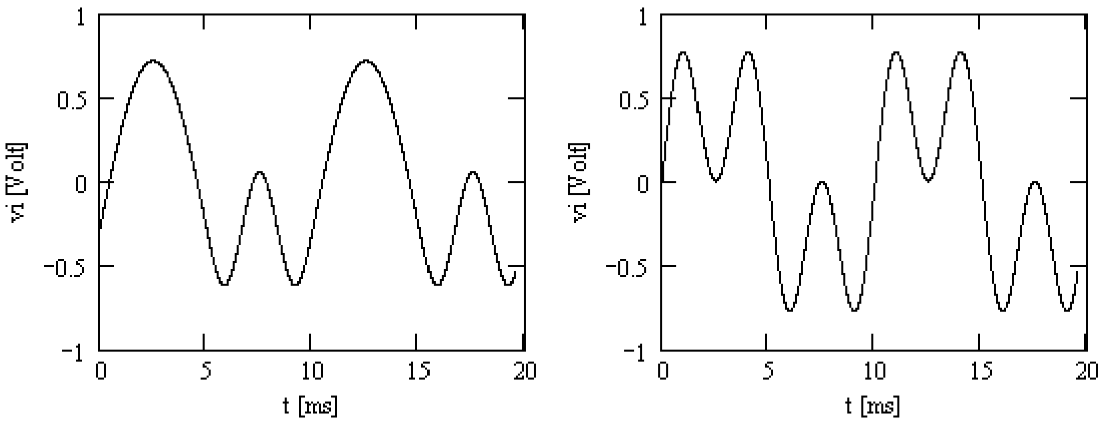
Trabajo Práctico: Diseño de un filtro

POULSEN KATRINE

Especificaciones



bt224 2013b La señal a la izquierda, de valor medio nulo, ingresa al filtro a diseñar produciendo como salida la señal de la derecha, que posee una amplitud Vpap de 1.54 Volt ; compuesta por 2 armónicos y un contenido residual de armónicos no deseados menor de 7mVolt RMS

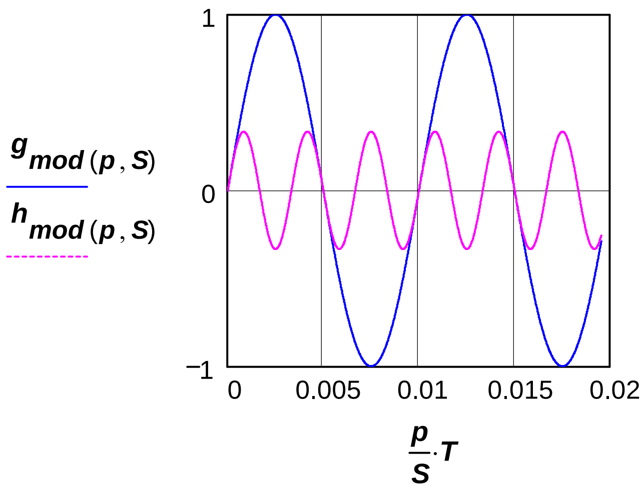
Defino las constantes y las variables:

$$(S \quad i \quad p \quad wo \quad T \quad k) := \left(1024 \quad 0..S-1 \quad 0..2000 \quad \frac{2\pi}{S} \quad \frac{1}{100} \quad 0..\frac{S}{2}\right)$$

Busqueda de valor medio

$$g_i := \sin(wo \cdot i) \cdot (0 \le i < S)$$

$$h_i := \frac{1}{3}\sin(3 \cdot wo \cdot i)(0 \le i < S)$$



Calculo la integral para que me de valor medio nulo en la señal de entrada

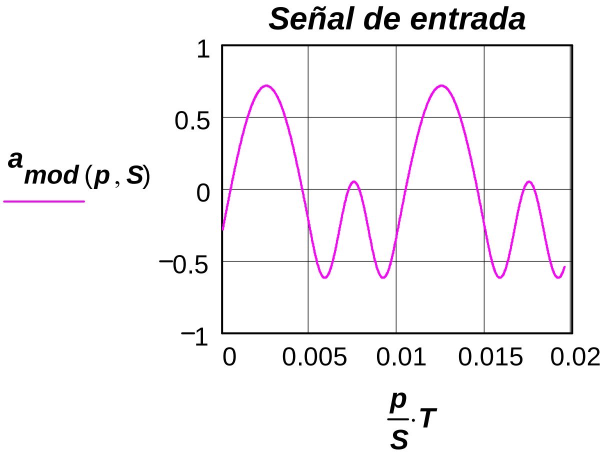
$$Vm := \left[\left(\int_0^5 sin\left(\frac{\pi \cdot 2 \cdot x}{5 \cdot 2}\right) dx\right) + \left(\int_5^{10} \frac{1}{3} \cdot sin\left(\frac{2\pi \cdot x}{\frac{10}{3}}\right) dx\right)\right] \cdot \frac{1}{10}$$

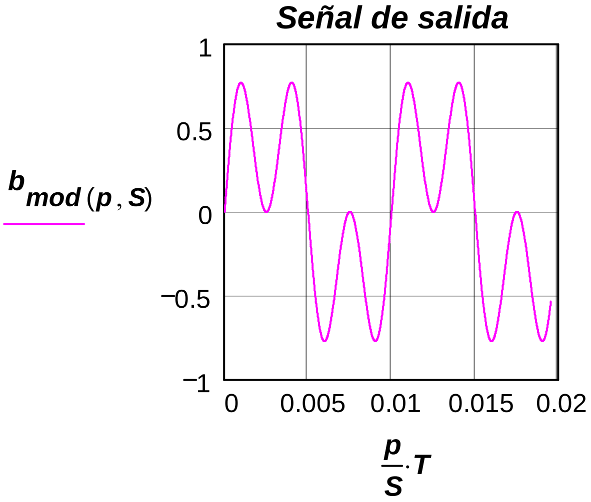
Defino señal de entrada

$$a_i := \left[sin(wo \cdot i) \cdot \left(0 \le i < \frac{S}{2}\right) + \frac{1}{3} \cdot sin(3 \cdot wo \cdot i) \cdot \left(\frac{S}{2} \le i < S\right)\right] - Vm$$

Defino señal de salida

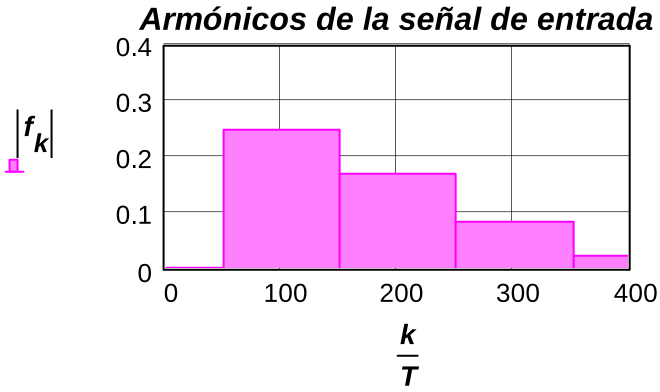
$$b_i := \frac{1}{2} sin(wo \cdot i) \cdot (0 \le i < S) + \frac{1}{2} \cdot sin(3 \cdot wo \cdot i)$$



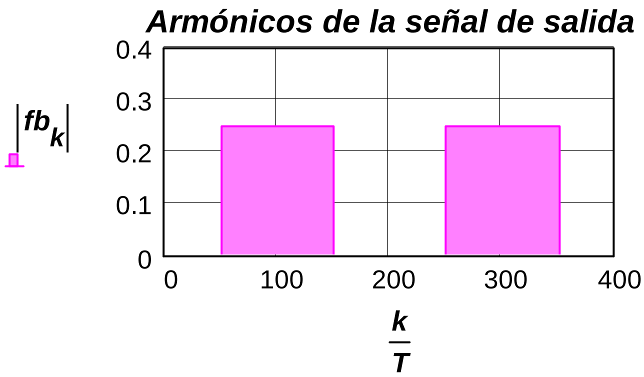


Determinación de armónicos mediante FFT

$f := FFT(a)$



$fb := FFT(b)$



$|f_0| = 5.013 \times 10^{-12}$

$|f_1| = 0.25$

$|f_2| = 0.17$

$|f_3| = 0.083$

$|fb_0| = 0$

$|fb_1| = 0.25$

$|fb_2| = 0$

$|fb_3| = 0.25$

Determinación por prueba y error de H(s)

$(A \quad w1 \quad Q1 \quad w2 \quad Q2 \quad w3 \quad fase) := \left[(6.37)^4 \quad 2 \cdot \pi \cdot 100 \quad 3.95 \quad 2\pi \cdot 300 \quad 9 \quad 2 \cdot \pi \cdot \right.$

$$H(s) := A\left(\frac{\frac{s\cdot w1}{Q1}}{s^2+\frac{s\cdot w1}{Q1}+w1^2}\right)^2\cdot\left(\frac{\frac{s\cdot w2}{Q2}}{s^2+\frac{s\cdot w2}{Q2}+w2^2}\right)^2\cdot\left[\frac{s^2+w3}{[s+(2-\sqrt{3})\cdot w3]\cdot[s}\right.$$

$$fas_k := H(2i\cdot\pi\cdot 100\cdot k)\cdot f_k \qquad fnas_k := fas_k\cdot(k\neq 1)\cdot(k\neq 3)$$

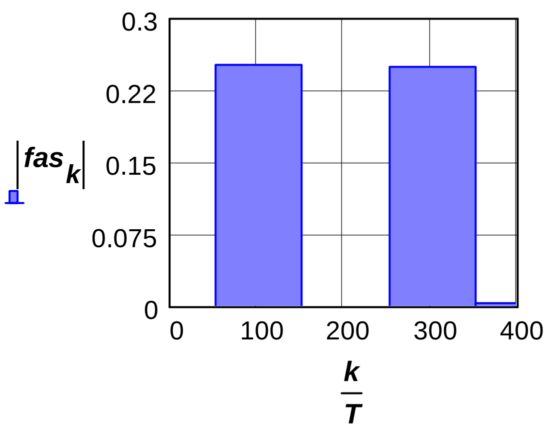
$$as := IFFT(fas) \qquad nas := IFFT(fnas)$$

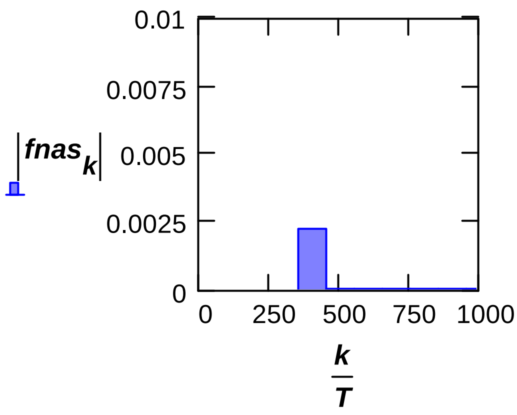
Ruido $stdev(nas) = 3.15\times 10^{-3}$

es menor que 0.007

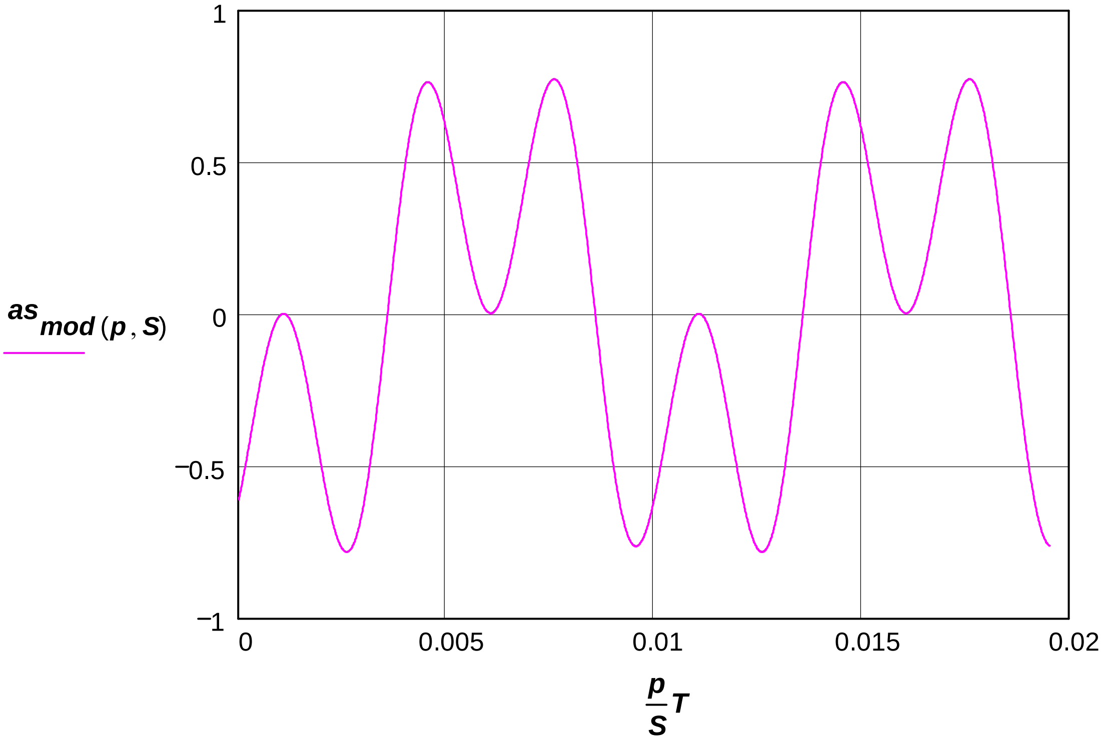
$$\frac{max(b)}{max(as)} = 0.996$$

es menor que 1

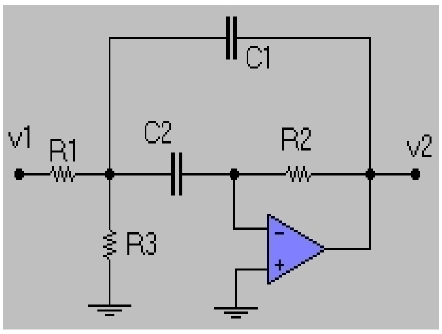




$|fas_1| = 0.25 \qquad |fas_3| = 0.25$



Pasabanda de 100Hz, Q=3,95 y ganancia 6,37



$C1a := 18 \cdot 10^{-9}$

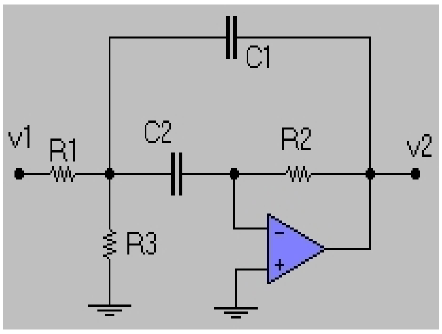
$C2a := 15 \cdot 10^{-9}$

$$sol := \begin{bmatrix} w1^2 = \frac{1}{C1a \cdot C2a \cdot R2a} \cdot \left(\frac{1}{R3a} + \frac{1}{R1a}\right) \\ \frac{w1}{Q1} = \left(\frac{1}{C1a} + \frac{1}{C2a}\right) \cdot \frac{1}{R2a} \\ \sqrt[4]{A} = \frac{1}{C1a \cdot R1a} \cdot \frac{Q1}{w1} \end{bmatrix} \left| \begin{array}{l} solve, \begin{pmatrix} R1a \\ R2a \\ R3a \end{pmatrix} \\ float, 3 \end{array} \right. \rightarrow \left(5.48 \cdot 10^4 \quad 7.6\right.$$

$$\begin{pmatrix} R1a \\ R2a \\ R3a \end{pmatrix} := \begin{pmatrix} 549 \cdot 10^{2} \\ 768 \cdot 10^{3} \\ 158 \cdot 10^{2} \end{pmatrix}$$

$$Ha(s) := \frac{\frac{-s}{C1a \cdot R1a}}{s^{2} + \left(\frac{1}{C2a} + \frac{1}{C1a}\right) \cdot \frac{1}{R2a} \cdot s + \frac{1}{C1a \cdot C2a \cdot R2a} \cdot \left(\frac{1}{R1a} + \frac{1}{R3a}\right)}$$

Pasabanda de 300Hz, Q=9 y ganancia 6,37



$$C1b := 56 \cdot 10^{-9}$$

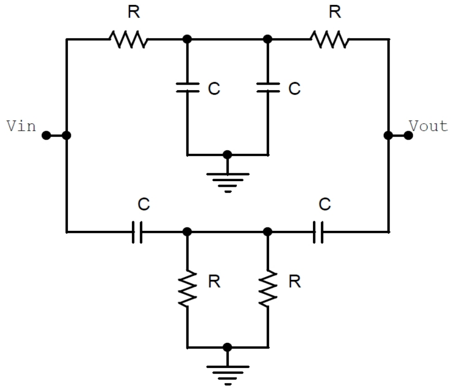
$$C2b := 10 \cdot 10^{-9}$$

$$sol := \begin{bmatrix} w2^{2} = \frac{1}{C1b \cdot C2b \cdot R2b} \cdot \left(\frac{1}{R3b} + \frac{1}{R1b}\right) \\ \frac{w2}{Q2} = \left(\frac{1}{C1b} + \frac{1}{C2b}\right) \cdot \frac{1}{R2b} \\ \sqrt[4]{A} = \frac{1}{C1b \cdot R1b} \cdot \frac{Q2}{w2} \end{bmatrix} \left| \begin{array}{l} solve, \begin{pmatrix} R1b \\ R2b \\ R3b \end{pmatrix} \\ float, 3 \end{array} \right. \rightarrow \left(1.34 \cdot 10^{4} \right.$$

$$\begin{pmatrix} R1b \\ R2b \\ R3b \end{pmatrix} := \begin{pmatrix} 133 \cdot 10^{2} \\ 562 \cdot 10^{3} \\ 953 \end{pmatrix}$$

$$Hb(s) := \frac{\frac{-s}{C1b \cdot R1b}}{s^{2} + \left(\frac{1}{C2b} + \frac{1}{C1b}\right) \cdot \frac{1}{R2b} \cdot s + \frac{1}{C1b \cdot C2b \cdot R2b} \cdot \left(\frac{1}{R1b} + \frac{1}{R3b}\right)}$$

Twint – t



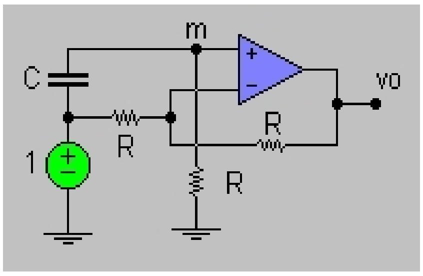
$\boldsymbol{Ct} := 18 \cdot 10^{-9}$

$\boldsymbol{sol} := \left(\boldsymbol{w3} = \dfrac{1}{\boldsymbol{Ct} \cdot \boldsymbol{Rt}}\right) \left| \begin{array}{l} \boldsymbol{solve}, \boldsymbol{Rt} \\ \boldsymbol{float}, 3 \end{array} \right. \rightarrow 4.42 \cdot 10^{4}$

$\boldsymbol{Rt} := 442 \cdot 10^{2}$

$$\boldsymbol{Ht}(\boldsymbol{s}) := \frac{\left[\boldsymbol{s}^2 + \left(\dfrac{1}{\boldsymbol{Ct} \cdot \boldsymbol{Rt}}\right)^2\right]}{\left[\boldsymbol{s} + (2 - \sqrt{3}) \cdot \left(\dfrac{1}{\boldsymbol{Ct} \cdot \boldsymbol{Rt}}\right)\right] \cdot \left[\boldsymbol{s} + (2 + \sqrt{3}) \cdot \left(\dfrac{1}{\boldsymbol{Ct} \cdot \boldsymbol{Rt}}\right)\right]}$$

Desfasaror Inversor



$\boldsymbol{Cf} := 22 \cdot 10^{-9}$

$$sol := \left(fase = \frac{1}{Cf \cdot Rf} \right) \Bigg| \begin{array}{l} solve, Rf \\ float, 3 \end{array} \rightarrow 3.82 \cdot 10^{4}$$

$$Rf := 324 \cdot 10^{2}$$

$$Hp(s) := \frac{s - \frac{1}{Cf \cdot Rf}}{s + \frac{1}{Cf \cdot Rf}}$$

***Comentario:** El cambio de resistencia se explica en las conclusiones al final.*

Transferencia normalizada: $Hn(s) := Ha(s)^{2} \cdot Hb(s)^{2} \cdot Ht(s) \cdot Hp(s)$

Comparación transferencia ideal versus normalizada:

$$H(s) \; float, 3 \rightarrow 1.83 \cdot 10^{12} \cdot \frac{s^{4}}{\left(s^{2} + 159. \cdot s + 3.94 \cdot 10^{5}\right)^{2} \cdot \left(s^{2} + 209. \cdot s + 3.55 \cdot 10^{6}\right)^{2}} \cdot$$

$$Hn(s) \; float, 3 \rightarrow 1.85 \cdot 10^{12} \cdot \frac{s^{4}}{\left(s^{2} + 159. \cdot s + 3.93 \cdot 10^{5}\right)^{2} \cdot \left(s^{2} + 210. \cdot s + 3.57 \cdot 10^{6}\right)^{2}}$$

Confirmación

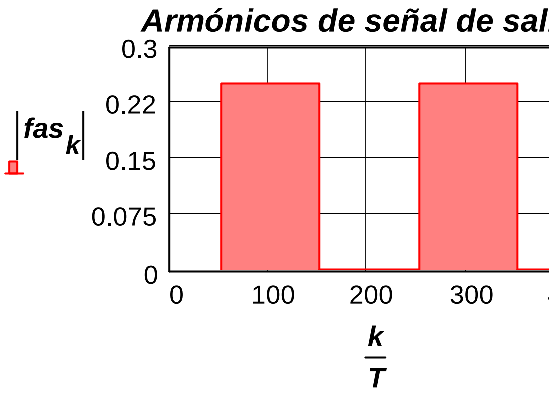
$$Hn(s) \rightarrow \frac{390625000000000000000000000}{21160653205041} \cdot \frac{s^{4}}{\left(s^{2} + \frac{34375}{216} \cdot s + \frac{1380859375000}{3513051}\right)^{2} \cdot \left(s^{2} + \frac{4\text{:}}{\text{:}}\right.}$$

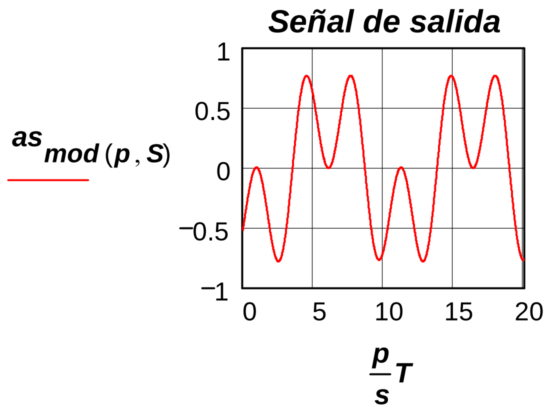
Recalculando amplitud y ruido con filtro normalizado

$fas_{k} := Hn(2i \cdot \pi \cdot 100 \cdot k) \cdot f_{k}$ $\qquad fnas_{k} := fas_{k} \cdot (k \neq 1) \cdot (k \neq 3)$

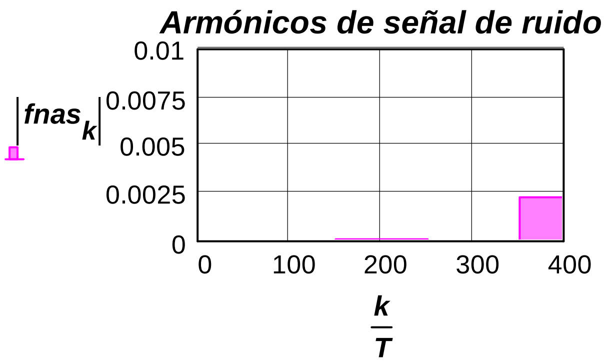
$as := IFFT(fas) \qquad nas := IFFT(fnas)$

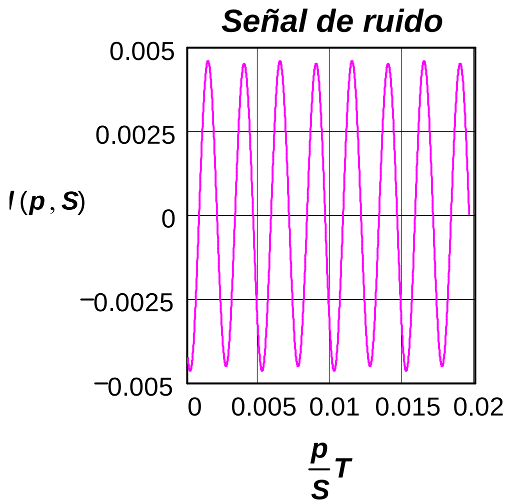
ruido $\quad stdev(nas) = 3.224 \times 10^{-3}$





$$|fas_1| = 0.25 \qquad |fas_3| = 0.251$$





Error porcentual en amplitudes

$$\left|\frac{|fb_1| - |fas_1|}{fb_1}\right| \cdot 100 = 0.147$$

$$\left|\frac{|fb_3| - |fas_3|}{fb_3}\right| \cdot 100 = 0.321$$

error menor al 1.5% y ruido menor a 7mV

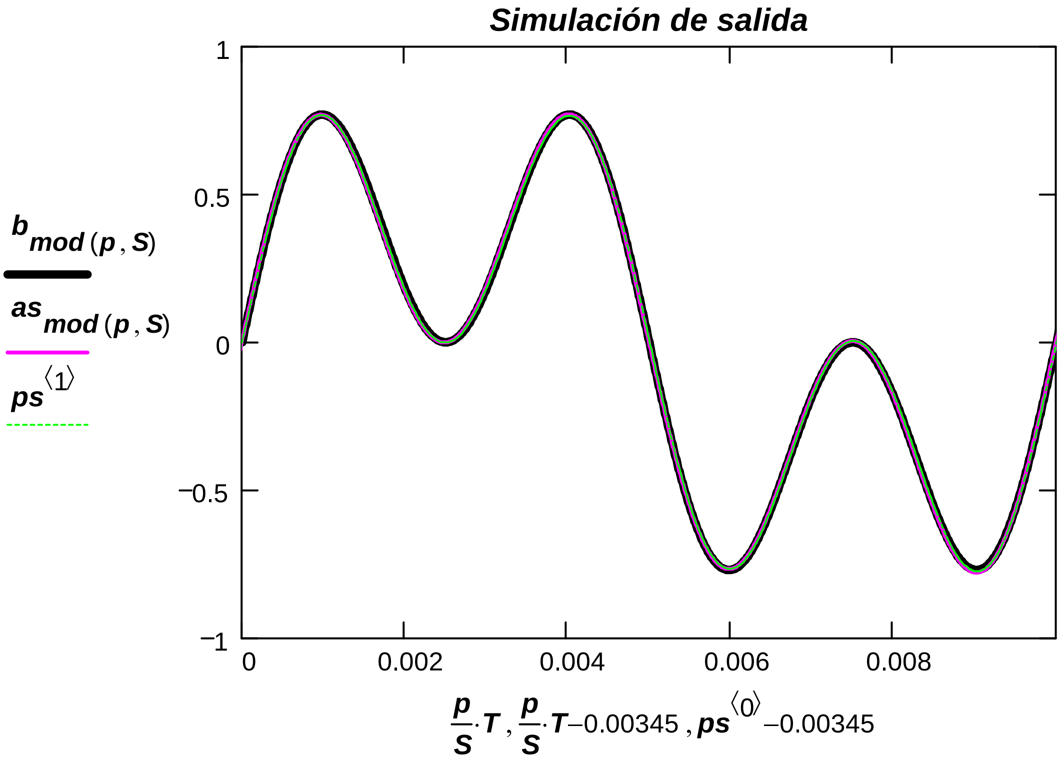
Circuito

Ver: Circuito.jpg

Superposición de la señal de salida teórica con valores normalizados con la simulada en LTspice

$ps :=$

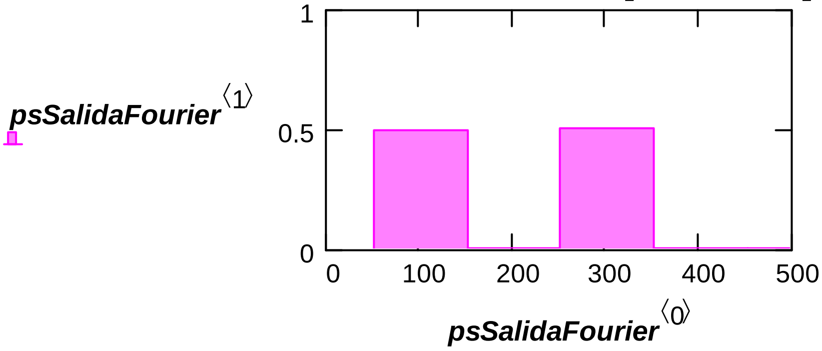
	0
0	0
1	$1.0895 \cdot 10^{-5}$
2	$2.179 \cdot 10^{-5}$
3	$3.2685 \cdot 10^{-5}$
4	$4.358 \cdot 10^{-5}$



$psSalidaFourier :=$

	0	1
0	100	0.4991
1	200	$3.242 \cdot 10^{-5}$
2	300	0.5004
3	400	0.0045
4	500	$4.138 \cdot 10^{-6}$
5	600	$5.326 \cdot 10^{-5}$
6	700	$5.565 \cdot 10^{-6}$
7	800	$3.8 \cdot 10^{-6}$
8	900	$4.825 \cdot 10^{-6}$
9	1000	$7.574 \cdot 10^{-7}$

Armónicos de salida [simulación]



$\left|psSalidaFourier_{0,1}\right| = 0.499$ $\left|psSalidaFourier_{2,1}\right| = 0.5$

Error porcentual en amplitudes con valores de la simulación de la señal de sali

$$\left|\frac{\left|fb_1\right| - \frac{\left|psSalidaFourier_{0,1}\right|}{2}}{fb_1}\right| \cdot 100 = 0.18$$

$\left|fb_1\right| = 0.25$ $\left|fb_3\right| = 0.25$

$$\left|\frac{\left|fb_3\right| - \frac{\left|psSalidaFourier_{2,1}\right|}{2}}{fb_3}\right| \cdot 100 = 0.08$$

error menor al 1.5%

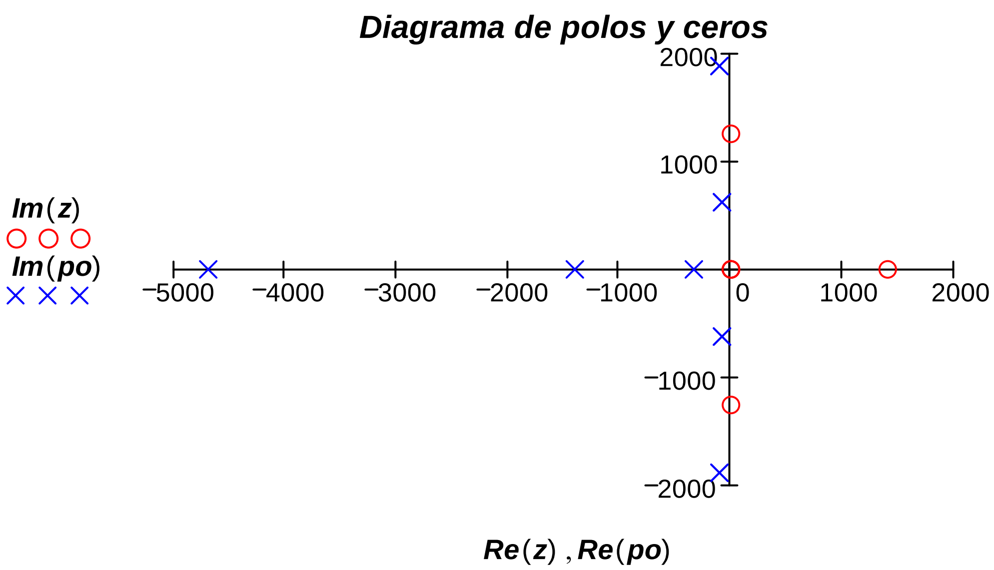
$$ruido := \sqrt{\frac{1}{2} \cdot \left[\sum_{j=0}^{19} \left(psSalidaFourier_{j,1}\right)^2 \cdot (j \neq 0) \cdot (j \neq 2)\right]}$$

$ruido = 3.206 \times 10^{-3}$ ***es menor que 7mv***

Aclaración: Simulé con LTSpice el desarrollo en serie de Fourier, con frecuencia fundamental 100Hz, para la señal de salida. Y en este caso el desarrollo de Fourier incrementa en un factor d los resultados, por eso en los calculos de erres porcentuales y ruido aparecen los factores de 1/

Diagrama de polos y ceros

$$z := Hn(u) \left| \begin{matrix} solve, u \\ float, 5 \end{matrix} \right. \rightarrow \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1256.9 \cdot i \\ -1256.9 \cdot i \\ 1402.9 \end{pmatrix} \qquad po := \frac{1}{Hn(u)} \left| \begin{matrix} solve, u \\ float, 5 \end{matrix} \right. \rightarrow \begin{pmatrix} -79.572 + 621.88 \cdot \\ -79.572 - 621.88 \cdot \\ -79.572 + 621.88 \cdot \\ -79.572 - 621.88 \cdot \\ -104.86 + 1887.3 \cdot \\ -104.86 - 1887.3 \cdot \\ -104.86 + 1887.3 \cdot \\ -104.86 - 1887.3 \cdot \\ -336.7 \\ -4690.9 \\ -1402.9 \end{pmatrix}$$



Puntos de 3dB [máximos]

Ver: 3db1 y 3db2

Diagrama de bode [amplitud]

$$db(x) := 20 \cdot log(|x|)$$

$$Hn(s) \ float, 4 \ \rightarrow 1.846 \cdot 10^{12} \cdot \frac{s^4}{\left(s^2 + 159.1 \cdot s + 3.931 \cdot 10^5\right)^2 \cdot \left(s^2 + 209.7 \cdot s + 3.573 \cdot 1\text{C}\right.}$$

$$w1 := \sqrt{3.931 \cdot 10^{5}} \quad w2 := \sqrt{3.573 \cdot 10^{6}} \quad w3a := 337. \quad w3b := 4691. \quad w3c := \sqrt{1.580 \cdot 10^{6}}$$

$$ko := \lim_{x \to 0} \frac{-Hn(x)}{x^{4}} \ \text{float}, 6 \ \rightarrow 9.35890 \cdot 10^{-13} \qquad w_k := 2 \cdot \pi \cdot 10 \cdot (300)^{\frac{k \cdot 2}{S}}$$

$$Hdb(x) := 20 \cdot \log\left(ko \cdot x^{4}\right) - 4 \cdot db\left(\frac{x}{w1}\right) \cdot (x > w1) - 4 \cdot db\left(\frac{x}{w2}\right) \cdot (x > w2) - db\left(\frac{\ }{w}\right.$$

$ps :=$

	0	1
0	0	0
1	10	-96.7039
2	10.1396	-96.2217
3	10.2811	-95.7394
4	10.4247	-95.2571
5	10.5702	-94.7748
6	10.7177	-94.2925
7	10.8673	-93.8101

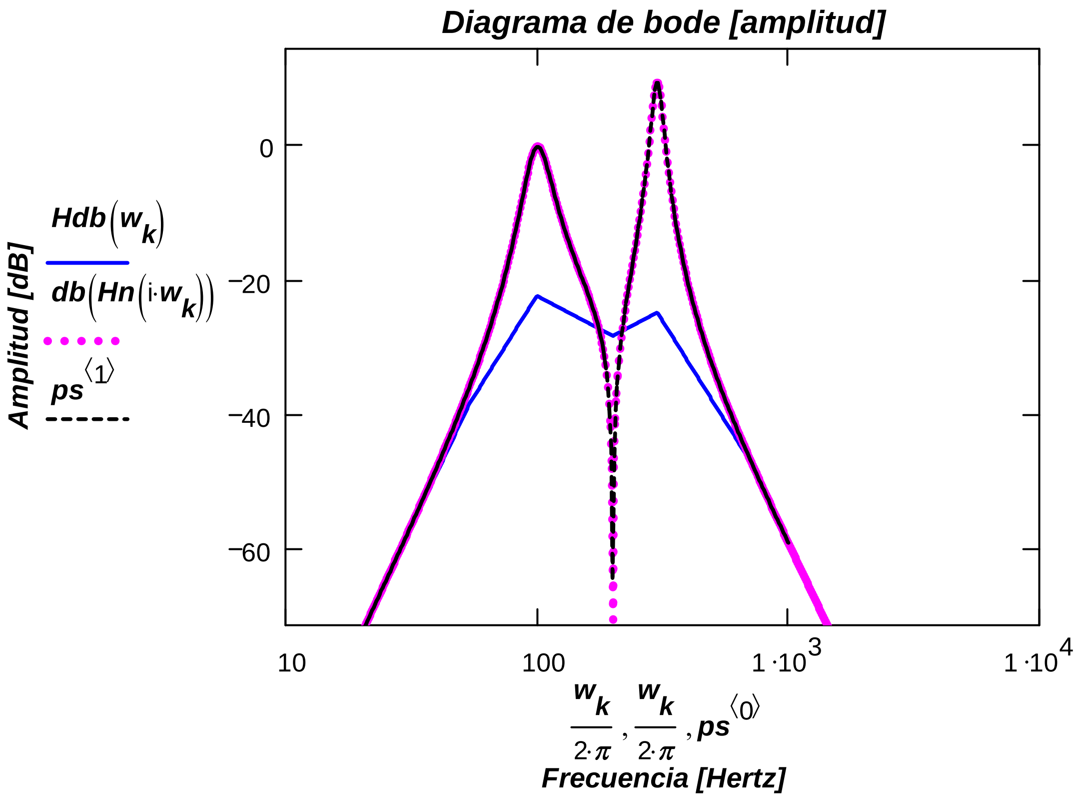


Diagrama de bode [fase]

$$b(x, xo) := if\left(x < \frac{xo}{10}, 0, if\left(x > 10 \cdot xo, -90, -45 - 45 \cdot log\left(\frac{x}{xo}\right)\right)\right)$$

$$Hc(s) := \left[\frac{s^2 + 1.580 \cdot 10^6}{(s + 337.) \cdot (s + 4691.)}\right] \qquad Hd(s) := \frac{s - 1187.}{s + 1187.}$$

$$Ha(s) := \frac{s}{\left(s^2 + 159.1 \cdot s + 3.931 \cdot 10^5\right)} \qquad Hb(s) := \frac{s}{\left(s^2 + 209.7 \cdot s + 3.573 \cdot 10^6\right)}$$

$$w_k := 2 \cdot \pi \cdot 1 \cdot (30000)^{\frac{k \cdot 2}{S}}$$

$$\phi gr(x) := 180 + 4 \cdot b\left(x, \sqrt{3.932 \cdot 10^5}\right) + 4 \cdot b\left(x, \sqrt{3.573 \cdot 10^6}\right) - 2 \cdot b\left(x, \sqrt{1.580 \cdot 10^6}\right)$$

$$\Phi gr(x) := \left[2 \cdot \left(arg(Ha(i \cdot x)) - \frac{\pi}{2}\right) + 2 \cdot \left(arg(Hb(i \cdot x)) - \frac{\pi}{2}\right) + (arg(Hc(i \cdot x))) + a\right.$$

$ps :=$

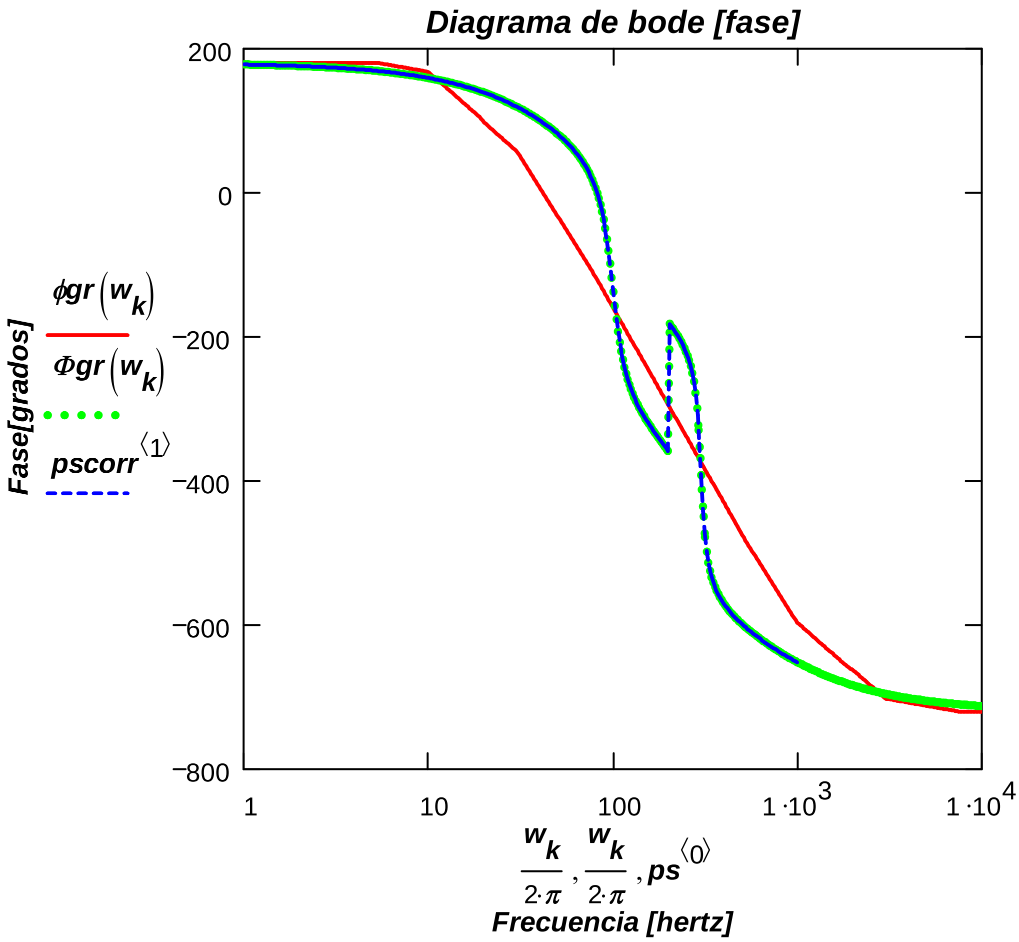
	0	1
0	1	177.9138
1	1.0233	177.8653
2	1.0471	177.8155
3	1.0715	177.7647
4	1.0965	177.7126
5	1.122	177.6593
6	1.1482	177.6048
7	1.1749	177.549
8	1.2023	177.4919
9	1.2303	177.4335

$$pscorr^{\langle 0 \rangle} := ps^{\langle 0 \rangle}$$

$$m := 0 .. 300$$

$$fase\_corr_m := \left(ps^{\langle 1 \rangle}\right)_m - 360 \cdot (m > 202) - 360 \cdot (m > 254)$$

$$pscorr^{\langle 1 \rangle} := fase\_corr$$

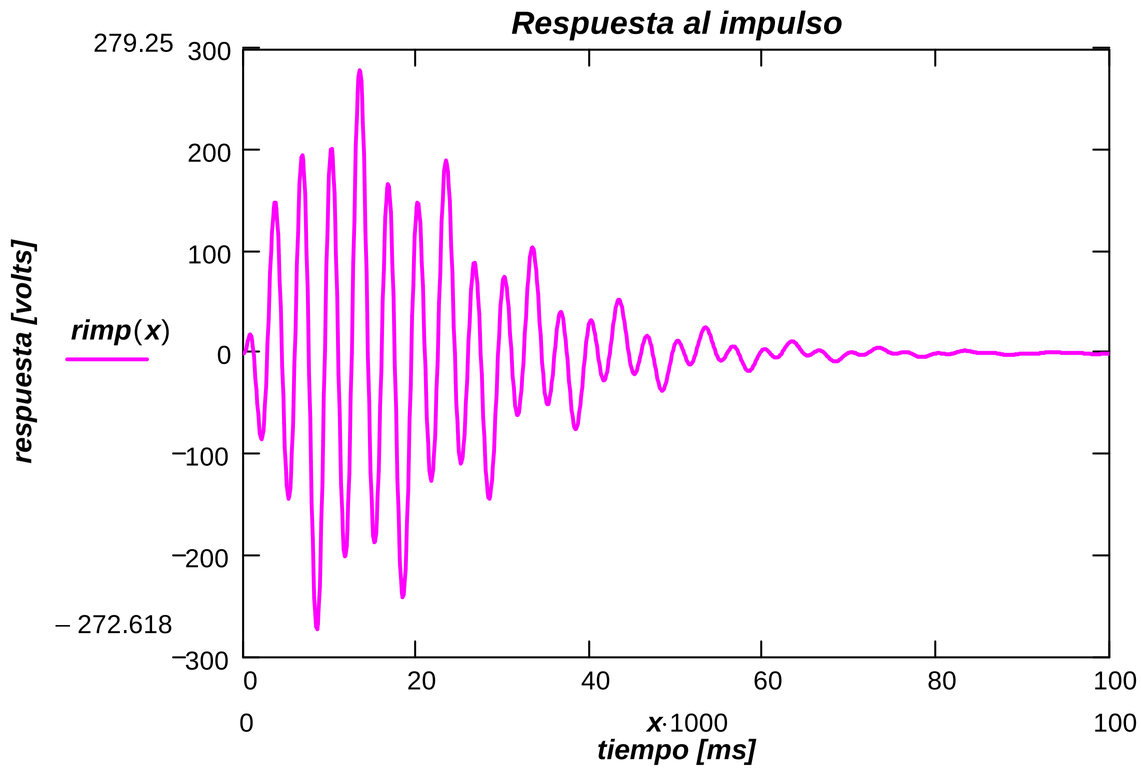


Respuesta al impulso

$$rimp(t) := Hn(s)\ \ invlaplace, s \ \rightarrow \frac{1113679736650168304332296683520000000000}{690109632628475527668769282456966498 7} \cdot$$

$$rimp(t) \left| \begin{array}{l} float, 2 \\ collect, cos, sin, exp \end{array} \right. \rightarrow \left(-86. + 7.2 \cdot 10^{4} \cdot t\right) \cdot exp\left(-1.0 \cdot 10^{2} \cdot t\right) \cdot cos\left(1.\right.$$

$$x := 0, \frac{1}{10000} .. \frac{1}{10}$$



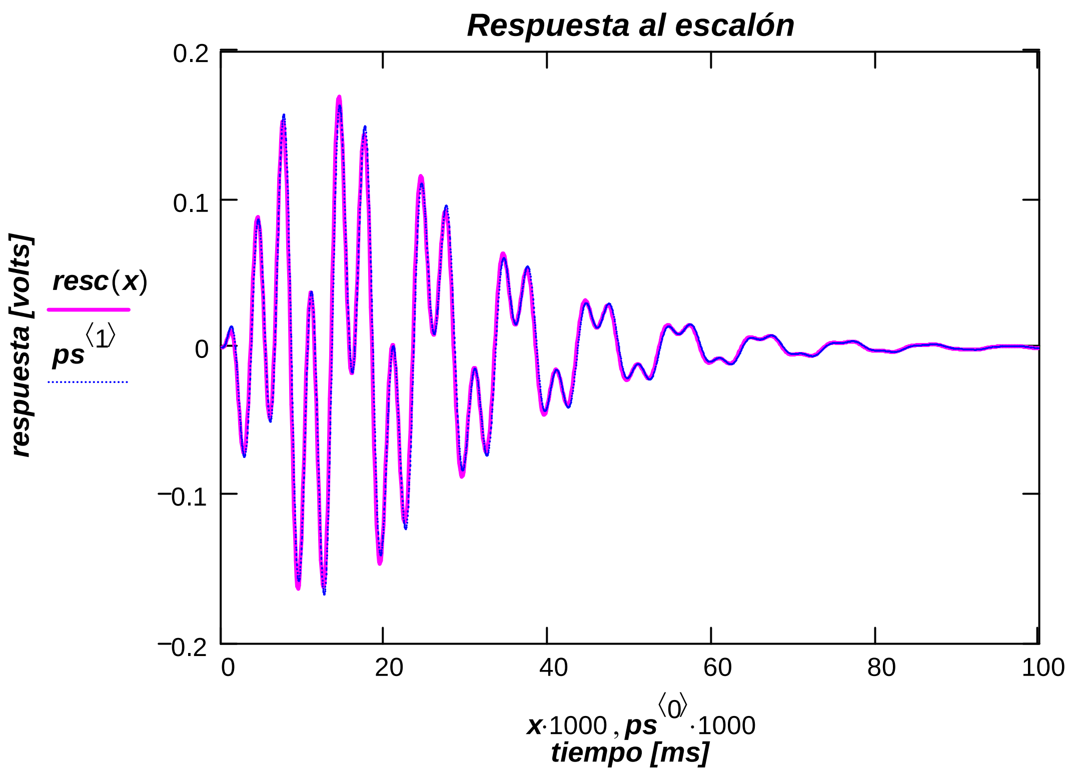
Respuesta al escalón

$$resc(t) := \frac{Hn(s)}{s}\ \textit{invlaplace}, s \rightarrow \frac{-793830916284239967328061076013056000}{690109632628475527668769282456966498 7} \cdot exp$$

$$resc(t) \ \Big|\ \begin{array}{l} \textit{float}, 3 \\ \textit{collect}, \sin, \cos, \exp \end{array} \rightarrow \left(-1.36 \cdot 10^{-2} - 7.26 \cdot t\right) \cdot exp(-79.6 \cdot t) \cdot \sin(623. \cdot$$

$ps :=$

	0	1
0	0	$-1.0071 \cdot 10^{-5}$
1	$10 \cdot 10^{-11}$	$-1.0071 \cdot 10^{-5}$
2	$1.5112 \cdot 10^{-10}$	$-1.0071 \cdot 10^{-5}$
3	$4.5782 \cdot 10^{-10}$	$-1.0071 \cdot 10^{-5}$
4	$8.6161 \cdot 10^{-10}$	$-1.0071 \cdot 10^{-5}$
5	$1.6692 \cdot 10^{-9}$	$-1.0071 \cdot 10^{-5}$
6	$3.2844 \cdot 10^{-9}$	$-1.0071 \cdot 10^{-5}$
7	$5.6785 \cdot 10^{-9}$	$-1.0071 \cdot 10^{-5}$
8	$9.2401 \cdot 10^{-9}$	$-1.0071 \cdot 10^{-5}$
9	$1.4017 \cdot 10^{-8}$	$-1.0071 \cdot 10^{-5}$



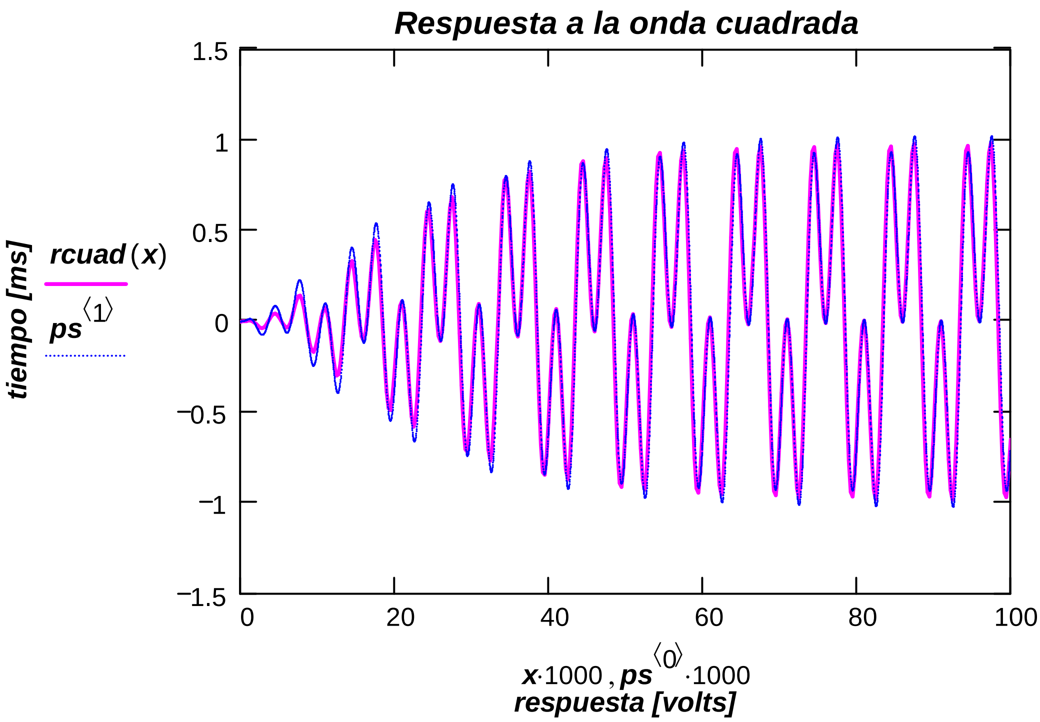
Respuesta a la onda cuadrada

$$x := 0, \left(\frac{1}{4000}\right) .. \frac{100}{1000}$$

$$rcuad(t) := \left[\sum_{j=0}^{20} \frac{(-1)^{j}}{s\cdot[1+(j=0)+(j=20)]}\cdot exp\left(-s\cdot j\cdot \frac{T}{2}\right)\right]\cdot Hn(s)\ \ invlapla$$

$ps :=$

	0	1
0	0	-1.0071·10 -5
1	10·10 -11	-1.0071·10 -5
2	1.5112·10 -10	-1.0071·10 -5
3	4.5782·10 -10	-1.0071·10 -5
4	8.6161·10 -10	-1.0071·10 -5
5	1.6692·10 -9	-1.0071·10 -5
6	3.2844·10 -9	-1.0071·10 -5
7	5.6785·10 -9	-1.0071·10 -5
8	9.2401·10 -9	-1.0071·10 -5
9	1.4017·10 -8	-1.0071·10 -5

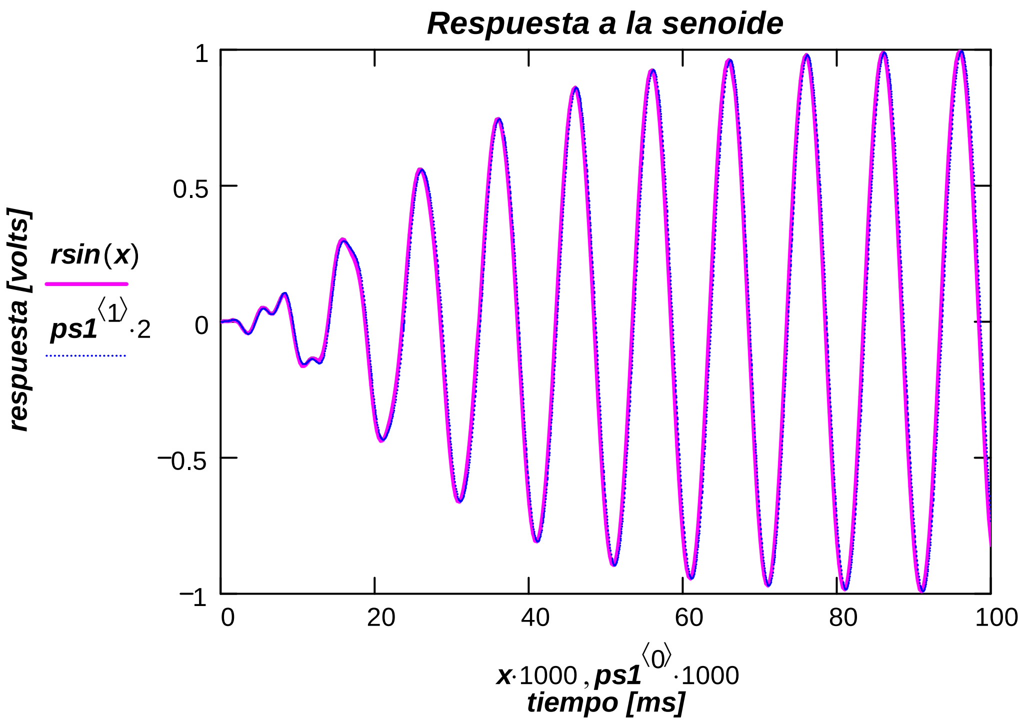


Respuesta a la senoide

$$rsin(t) := \frac{\frac{2\cdot\pi}{T}}{s^2 + \left(2\cdot\frac{\pi}{T}\right)^2} \cdot Hn(s) \ \ invlaplace, s \ \rightarrow$$

$ps1 :=$

	0	1
0	0	$-1.0071\cdot10^{-5}$
1	$1.2046\cdot10^{-7}$	$-1.0071\cdot10^{-5}$
2	$2.4092\cdot10^{-7}$	$-1.0071\cdot10^{-5}$
3	$3.6137\cdot10^{-7}$	$-1.0071\cdot10^{-5}$
4	$4.8183\cdot10^{-7}$	$-1.0071\cdot10^{-5}$
5	$6.0229\cdot10^{-7}$	$-1.0071\cdot10^{-5}$
6	$7.2275\cdot10^{-7}$	$-1.0071\cdot10^{-5}$
7	$8.432\cdot10^{-7}$	$-1.0071\cdot10^{-5}$
8	$4.3959\cdot10^{-6}$	$-1.0071\cdot10^{-5}$
9	$8.4394\cdot10^{-6}$	$-1.0071\cdot10^{-5}$



Conclusiones: En primera instancia se determina que la señal de salida está compuesta por dos armónicos de la señal de entrada, que se encuentran a 100Hz y 300Hz. Se continua con la construcción de la transferencia, utilizando 2 pasa-banda para los armónicos de 100Hz y 300Hz. Esto filtros se colocan 2 veces en cascada. Se utiliza un Twint-t para eleminar el armónico de 400Hz que e el que genera más ruido en la señal de salida y por último un desfasador para ajustar la forma de la señal.

A continuación se procede a normalizar la transferencia, se observa que la transferencia H(s) y la transferencia normalizada Hn(s) son diferentes, pero es muy poca la variación, por lo tanto se puede analizar que la elección de componentes fue apropiada.

Otro comentario importante es que al realizar la simulación en LTSpice, para observar el resultado del análisis de Fourier, el programa incrementa el resultado en un factor de 2, por lo tanto si comparamos los armónicos obtenidos teóricamente son 0.25 los dos, y los obtenidos en la simulación son 0.49 y 0.50, es decir 0.25*2 aproximadamente en ambos casos. Esto prueba que los resultados concuerdan, además que de 400Hz en adelante las frecuencias son muy bajas, es decir prácticamente nulas, com se esperaba.

El valor de la resistencia en el circuito desfasador, tuvo que ser modificado del que daba teóricamente porque al graficar la seña de salida, se veía una diferencia en los picos entre las señales de salida normalizada y la planetada en el comienzo del trabajo, por eso se tomó una R=32.4k que como se ve da una salida con mejores resultados.

Y para finalizar como tanto en la simulación como en la normalización de la transferencia se consiguieron errores de amplitud menores al 1,5% y ruido menor a 7mv, los resultados son satisfactorios.

$$\cdot\ 200 \quad 2 \cdot \pi \cdot 190 \;\Big]$$

$$\left.\frac{\ldots 3^2}{\ldots + (2+\sqrt{3})\cdot \boldsymbol{w3}\,]}\right]\cdot\left(\frac{\boldsymbol{s}-\boldsymbol{fase}}{\boldsymbol{s}+\boldsymbol{fase}}\right)$$

$\text{;}8 \cdot 10^5 \quad 1.57 \cdot 10^4)$

$5.63 \cdot 10^{5} \quad 957.\,)$

$$\frac{s^2 + 1.58 \cdot 10^6}{(s + 339.) \cdot \left(s + 4.68 \cdot 10^3\right)} \cdot \frac{s - 1.19 \cdot 10^3}{s + 1.19 \cdot 10^3}$$

$$\cdot \frac{s^2 + 1.58 \cdot 10^6}{\left(s + 3.3 \cdot 10^2\right) \cdot \left(s + 4.69 \cdot 10^3\right)} \cdot \frac{s - 1.40 \cdot 10^3}{s + 1.40 \cdot 10^3}$$

$$\frac{}{\frac{12500}{1967} \cdot s + \frac{890812500000000}{249315283}\Big)^2} \cdot \frac{s^2 + \frac{6250000000000}{3956121}}{\left(s + \frac{5000000}{1989} - \frac{2500000}{1989} \cdot 3^{\frac{1}{2}}\right) \cdot \Big(s + \frac{5000000}{1989} + \frac{2500000}{1989}}$$

$$\begin{pmatrix} i \\ i \\ i \\ i \\ i \\ i \\ i \\ i \end{pmatrix}$$

$$\frac{\quad}{)^6)^2} \cdot \frac{s^2 + 1.580 \cdot 10^6}{(s + 337.) \cdot (s + 4691.)} \cdot \frac{s - 1403.}{s + 1403.}$$

$$\left.\frac{\boldsymbol{x}}{\boldsymbol{w3a}}\right) \cdot (\boldsymbol{x} > \boldsymbol{w3a}) - \boldsymbol{db}\left(\frac{\boldsymbol{x}}{\boldsymbol{w3b}}\right) \cdot (\boldsymbol{x} > \boldsymbol{w3b}) + 2 \cdot \boldsymbol{db}\left(\frac{\boldsymbol{x}}{\boldsymbol{w3c}}\right) \cdot (\boldsymbol{x} > \boldsymbol{w3c})$$

$$+ \boldsymbol{b}(\boldsymbol{x}, 337.) + \boldsymbol{b}(\boldsymbol{x}, 4691.) + 2 \cdot \boldsymbol{b}(\boldsymbol{x}, 1187)$$

$$\boldsymbol{rg}(\boldsymbol{Hd}(\boldsymbol{i} \cdot \boldsymbol{x}))\Big] \cdot \frac{180}{\pi}$$

$$exp\left(\frac{-1250000}{891}\cdot t\right) - \frac{116547686260276499369240380101485623561061425181841149553484 21}{625463507534309178048374683657398543340470890319093142953455 8}$$

$$9\cdot 10^{3}\cdot t\big) + \big(-2.6\cdot 10^{3}\cdot t - 38.\big)\cdot exp(-80.\cdot t)\cdot cos\big(6.2\cdot 10^{2}\cdot t\big) + \big(15. + 1.5\cdot 10^{4}\cdot t\big)\cdot exp\big(-$$

$$\left(\frac{-1250000}{891}\cdot \boldsymbol{t}\right)+\frac{73285336284597491050545520258403924170187804847878367743503963 17}{6254635075343091780483746836573985433404708903190931429534558 5736}$$

$$\boldsymbol{t})+\left(37.8\cdot \boldsymbol{t}-3.96\cdot 10^{-2}\right)\cdot \boldsymbol{exp}(-105.\cdot \boldsymbol{t})\cdot \boldsymbol{sin}\left(1.88\cdot 10^{3}\cdot \boldsymbol{t}\right)+\left(7.73\cdot 10^{-2}-23.5\cdot \boldsymbol{t}\right)\cdot \boldsymbol{exp}(-$$

ace , *s* $\rightarrow$

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$$\frac{}{\cdots 3^{\frac{1}{2}})} \cdot \frac{s - \frac{1250000}{891}}{s + \frac{1250000}{891}}$$

$$\frac{.43281520640000000000000000}{57365814725196057023085 07}\cdot \boldsymbol{exp}\left[\frac{}{4555835875802274005633119796610958383926501223796}\right.$$

$$\cdot 1.0\cdot 10^{2}\cdot \boldsymbol{t}\big)\cdot \boldsymbol{sin}\big(1.9\cdot 10^{3}\cdot \boldsymbol{t}\big)+\big(-53.+1.5\cdot 10^{4}\cdot \boldsymbol{t}\big)\cdot \boldsymbol{exp}(-80.\cdot \boldsymbol{t})\cdot \boldsymbol{sin}\big(6.2\cdot 10^{2}\cdot \boldsymbol{t}\big)+1.6\cdot 10$$

$$\frac{17076841267200000000}{58147251960570230850\,7} \cdot \boldsymbol{exp}\left[\frac{1}{94913247412547375117356662429394966331802108829092121\text{9}}\right.$$

$$79.6 \cdot \boldsymbol{t}) \cdot \boldsymbol{cos}(623. \cdot \boldsymbol{t}) + \left(-9.95 \cdot \boldsymbol{t} + 1.43 \cdot 10^{-2}\right) \cdot \boldsymbol{exp}(-105. \cdot \boldsymbol{t}) \cdot \boldsymbol{cos}\left(1.88 \cdot 10^{3} \cdot \boldsymbol{t}\right) - .115 \cdot \boldsymbol{ex}$$

$$\frac{1}{\text{ʖ}421855472743043093037677300869454038833850097656 25} \cdot \Big(-114525788733088838753974856$$

$$^{2} \cdot \boldsymbol{exp}\left(-1.4 \cdot 10^{3} \cdot \boldsymbol{t}\right) - 6. \cdot \boldsymbol{exp}\left(-3. \cdot 10^{2} \cdot \boldsymbol{t}\right) - 32. \cdot \boldsymbol{exp}\left(-4.7 \cdot 10^{3} \cdot \boldsymbol{t}\right)$$

$$\overline{}\ \cdot \Bigg(-2385953931939350807374476179$$
$$9890154800644382849437681136258090385437011718750000$$

$$xp\left(-1.40 \cdot 10^{3} \cdot \boldsymbol{t}\right) + 1.67 \cdot 10^{-2} \cdot \boldsymbol{exp}\left(-3.3 \cdot 10^{2} \cdot \boldsymbol{t}\right) + 6.73 \cdot 10^{-3} \cdot \boldsymbol{exp}\left(-4.69 \cdot 10^{3} \cdot \boldsymbol{t}\right)$$

$626720924683924113217607387015403294195400645482676456863721313476562500000 + 5726$

972335259758175235870015389615423529573751344755575951799419403076171875000000000 -

62894366544419376987428313360462341962056608803693507701647097700322741338228431866

⊢ 119297696596967540368723808986167629879087617935007694807711764786875672377787975

$$06567382812500000 \cdot 3^{\frac{1}{2}}\Big) \cdot \boldsymbol{t}\Big] + \frac{46994026350240688262858124920010055321004330024077 1197}{62546350753430917804837468365739854334047089031909314 2}$$

$$5899709701538085937500000000 \cdot 3^{\frac{1}{2}}\Big) \cdot \boldsymbol{t}\Big] + \frac{179484444601729997343077980360219620783983}{625463507534309178048374683657398543340470}$$

$$\frac{528071554664185856000000000000000}{2953455857365814725196057023085O7} \cdot \boldsymbol{exp}\left[\frac{}{4555835875802274005633119796610958383926 50}\right.$$

$$\frac{7994036130563408529514131252871168000000000}{9031909314295345585736581472519605702308507} \cdot \boldsymbol{exp}\left[\frac{}{949132474125473751173566624293949}\right.$$

$$\frac{1}{122379642185547274304309303767730086945403883385009765625} \cdot \Big(-1145257887330888387 5$$

$$\frac{1}{966331802108829092121989015480064438284943768113625809038543701171875000} \cdot \Big(-238595$$

39748566267209246839241132176073870154032941954006454826764568637213134765625000000

393193935080737447617972335259758175235870015389615423529573751344755575951799419

$0 + 5726289436654441937698742831336046234196205660880369350770164709770032274133822$

$403076171875000000000 + 1192976965969675403687238089861676298790876179350076948077l$

$$2843186065673828125000000 \cdot 3^{\frac{1}{2}}\Big) \cdot \boldsymbol{t}\Big] \cdot 3^{\frac{1}{2}} - \frac{1165476862602764993692403801014856235610614\ldots}{6254635075343091780483746836573985433404708\ldots}$$

$$176478687567237778797589970970153808593750000000 \cdot 3^{\frac{1}{2}}\Big) \cdot \boldsymbol{t}\Big] \cdot 3^{\frac{1}{2}} + \frac{73285336284597491}{625463507534309178}$$

$$\frac{2518184114955348421432815206400000000000000000}{39031909314295345585736581472519605702308507} \cdot \boldsymbol{exp}\left[\frac{}{4555835875802274005633119796610}\right.$$

$$\frac{0505455202584039241701878048478783677435039631717076841267200000000}{0483746836573985433404708903190931429534558573658147251960570230850 7} \cdot \boldsymbol{exp}\left[\frac{}{9491324} \right.$$

$$\frac{-1}{0958383926501223796421855472743043093037677300869454038833850097656\,25} \cdot \Bigg(1145257887$$

$$\frac{-1}{47412547375117356662429394966331802108829092121989015480064438284943768113625809038}$$

3308883875397485662672092468392411321760738701540329419540064548267645686372131347

$$\frac{}{3543701171875000} \cdot \left(23859539319393508073744761797233525975817523587001538961542352 9 \right.$$

$765625000000 + 5726289436654441937698742831336046234196205660880369350770164709770003$

$5737513447555759517994194030761718750000000000 + 11929769659696754036872380898616762$

$$3227413382284318606567382812500000 \cdot 3^{\frac{1}{2}}\Big) \cdot \boldsymbol{t}\Big] - \frac{46994026350240688262858124920010055 32}{625463507534309178048374683657398543 3}$$

$$2987908761793500769480771176478687567237778797589970970153808593750000000 \cdot 3^{\frac{1}{2}}\Big) \cdot \boldsymbol{t}\Bigg]$$

$$\frac{100433002407711975280715546641858560000000000000000}{3404708903190931429534558573658147251960570230850 7} \cdot \boldsymbol{exp}\left[\frac{}{45558358758022740056331 19}\right.$$

$$-\frac{17948444460172999734307798036021962078398379940361305634085295141312528711680000}{62546350753430917804837468365739854334047089031909314295345585736581472519605702}$$

$$\frac{-1}{79661095838392650122379642185547274304309303767730086945403883385009765625} \cdot \Big(11452$$

$$\frac{000000}{2308507} \cdot \boldsymbol{exp}\left[\frac{-1}{94913247412547375117356662429394966331802108829092121989015480064438}\right.$$

25788733088838753974856626720924683924113217607387015403294195400645482676456863721

$$\frac{}{284943768113625809038543701171875000} \cdot \Big(2385953931939350807374476179723352597581752$$

$13134765625000000 + 5726289436654441937698742831336046234196205660880369350770164\!70$

$3587001538961542352957375134475557595179941940307617187500000000 + 119297696596967$

$$9770032274133822843186065673828125000000 \cdot 3^{\frac{1}{2}}\Big) \cdot \boldsymbol{t}\Big] \cdot 3^{\frac{1}{2}} - \frac{4531047334734988712331001324}{1188016211824532321860202286}$$

75403687238089861676298790876179350076948077117647868756723777879758997097015380859

$$\frac{46864516489418930451546058514043951704850723978369026944545366659279590812665183738}{56665008260192714591937526366720195583797431611677303379213007224620495897979449025}$$

$$937500000000 \cdot 3^{\frac{1}{2}}\Big) \cdot \boldsymbol{t}\Big] \cdot 3^{\frac{1}{2}} + \frac{4592811574988797797703078681782660566016209944665946549}{5940081059122661609301011433325041300963572959687631833}$$

$$\frac{326560000}{26397629} \cdot \boldsymbol{exp}\left(\frac{-34375}{432} \cdot \boldsymbol{t}\right) \cdot \boldsymbol{cos}\left(\frac{3125}{2081808} \cdot 171630135519^{\frac{1}{2}} \cdot \boldsymbol{t}\right) - \frac{4012674126013695534}{3064108824778028370870}$$

$$\frac{01010566886035258385110418019487322211135000489522921809492 3776}{600977918987158058386516896065036123102479489897245126319881 45} \cdot \boldsymbol{exp}\left(\frac{-34375}{432} \cdot \boldsymbol{t}\right) \cdot \boldsymbol{c}$$

$$\frac{46931299849168844304438458926817704728191005312194965008874715319056701959181807675}{77218730355438363280565611379950073758812992988359059442169394256306307396084776397}$$

$$\boldsymbol{os}\left(\frac{3125}{2081808}\cdot 171630135519^{\frac{1}{2}}\cdot \boldsymbol{t}\right)-\frac{274279920053997401016817225323700819300199434\mathrm{C}}{837188203491264582206890363485092448983761096005\mathrm{4}}$$

$$\frac{540316542389259047750860800000}{780586001651241708643445518923} \cdot \boldsymbol{exp}\left(\frac{-34375}{432} \cdot \boldsymbol{t}\right) \cdot 171630135519^{\frac{1}{2}} \cdot \boldsymbol{sin}\left(\frac{3125}{2081808} \cdot 1716\right.$$

$$\frac{961840896443685037994472901933891197025498177148207382769665474685968944021504}{508398248122931662183222519588508897011768841761684147010546493203325372771736390 5}$$

$$30135519^{\frac{1}{2}} \cdot \boldsymbol{t}\Bigg) + \frac{71059060632361625560797498991067897647349330115757469193480223129}{193419415308803679104660241277120981601962927263512593851728105677}$$

$$\cdot \boldsymbol{exp}\left(\frac{-34375}{432}\cdot \boldsymbol{t}\right)\cdot 171630135519^{\frac{1}{2}}\cdot \boldsymbol{sin}\left(\frac{3125}{2081808}\cdot 171630135519^{\frac{1}{2}}\cdot \boldsymbol{t}\right)-\frac{338498414192}{193419415308803}$$

$$\frac{6000000000000}{87669810106801} \cdot \boldsymbol{exp}\left(\frac{-34375}{432} \cdot \boldsymbol{t}\right) \cdot \boldsymbol{t} \cdot 171630135519^{\frac{1}{2}} \cdot \boldsymbol{sin}\left(\frac{3125}{2081808} \cdot 171630135519^{\frac{1}{2}} \cdot \boldsymbol{t}\right) -$$

$$\frac{7403723814137042308061671182229744870863395717469467443200000000}{67910466024127712098160196292726351259385172810567787669810106801} \cdot \boldsymbol{exp}\left(\frac{-34375}{432} \cdot \boldsymbol{t}\right.$$

$$-\frac{137615595717624293221146994042706969120098445679502974596340876355556147200000000}{522232421333769933582582651448226650325299903611484003399665885330267084872883}$$

$$\Big) \cdot \boldsymbol{t} \cdot 171630135519^{\frac{1}{2}} \cdot \boldsymbol{sin}\left(\frac{3125}{2081808} \cdot 171630135519^{\frac{1}{2}} \cdot \boldsymbol{t}\right) - \frac{7466176466102468799245022036\,8}{3170810087029568509912462971\,7}$$

$$\frac{00000}{627} \cdot \boldsymbol{exp}\left(\frac{-34375}{432} \cdot \boldsymbol{t}\right) \cdot \boldsymbol{t} \cdot \boldsymbol{cos}\left(\frac{3125}{2081808} \cdot 171630135519^{\frac{1}{2}} \cdot \boldsymbol{t}\right) - \frac{2038205619032914253737}{2370833861023310587637}$$

$$\frac{383581156822256373805488785444496791735500800000000}{7560816656059496272706982598643951750471589852634 1} \cdot \boldsymbol{exp}\left(\frac{-34375}{432} \cdot \boldsymbol{t}\right) \cdot \boldsymbol{t} \cdot \boldsymbol{cos}\left(\frac{3125}{20818}\right.$$

$$\frac{3930257734921643216892534187569287943898808525699183260634888412173884735584273561}{3853180033036334246562975936713350298715113758988672499942385345681206814245947566}$$

$$\frac{5}{08} \cdot 171630135519^{\frac{1}{2}} \cdot \boldsymbol{t} \Big) + \frac{169238991101653997816093185440466590077242015181079556220 3}{118541693051165529381692659001651816712328148796835667514 93}$$

$$\frac{401388965515587801175636705280000}{869312048321258905078607226230 73} \cdot \boldsymbol{exp}\left(\frac{-206250}{1967} \cdot \boldsymbol{t}\right) \cdot \boldsymbol{cos}\left(\frac{6250}{10008227789} \cdot 9133837918\right.$$

$$\frac{304765693569721551542192138351843065811733559092531653277189131864813667450 88}{357556879494336249971192672840603407122973783434656024160629452539303613115365} \cdot \boldsymbol{ex}$$

$$\left. 051481079^{\frac{1}{2}} \cdot \boldsymbol{t} \right) + \frac{7055932495033879033625620227738843272039787941259978099891661}{142987664109713860035824353829027852412663728525947197350606788366}$$

$$\boldsymbol{p}\left(\frac{-206250}{1967}\cdot \boldsymbol{t}\right)\cdot \boldsymbol{cos}\left(\frac{6250}{10008227789}\cdot 913383791805148107 9^{\frac{1}{2}}\cdot \boldsymbol{t}\right)-\frac{7023400384533117}{5375476094350145114128}$$

$$\frac{1532372224423592201441003406414814990893230858467439335604648602064181014486122496}{6397531475446955982855083879776784202213427937567072327244084960042121261766006587}$$

$$\frac{8583971648358712580708457354264831985418538364094204388891565817897006471188336467}{37351063544305418294634784190675695716837731819456070505524661009589619540480609105}$$

$$\frac{0000}{701461429} \cdot \boldsymbol{exp}\left(\frac{-206250}{1967} \cdot \boldsymbol{t}\right) \cdot 9133837918051481079^{\frac{1}{2}} \cdot \boldsymbol{sin}\left(\frac{6250}{10008227789} \cdot 91338379180514\right.$$

$$\frac{941503605134345823213118414683175202190999552}{5767967577709485986619735339929370743082954399045 65} \cdot \boldsymbol{exp}\left(\frac{-206250}{1967} \cdot \boldsymbol{t}\right) \cdot 91338379180$$

$$81079^{\frac{1}{2}} \cdot \boldsymbol{t}\Bigg) + \frac{861397691126149912171274796583388793008917546210262026969634050234}{175678221976666892049041525896780614155290078888625287765047016645331}$$

$$51481079^{\frac{1}{2}} \cdot \boldsymbol{sin}\left(\frac{6250}{10008227789} \cdot 9133837918051481079^{\frac{1}{2}} \cdot \boldsymbol{t}\right) + \frac{21925130128876533676613}{175678221976666892049041525}$$

$$\frac{1369856000000000000}{5957461476863965686719} \cdot \boldsymbol{exp}\left(\frac{-206250}{1967} \cdot \boldsymbol{t}\right) \cdot \boldsymbol{t} \cdot 9133837918051481079^{\frac{1}{2}} \cdot \boldsymbol{sin}\left(\frac{6250}{10008227789}\right.$$

$$\frac{69754544030877778693298593335800407238317841046274048000000 0}{896780614155290078888625287765047016645331595746147686396568671 9} \cdot \boldsymbol{exp}\left(\frac{-206250}{1967} \cdot \boldsymbol{t}\right)$$