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MEASUREMENT SPECIALTIES

# Piezo Film Sensors

# Technical Manual

## Internet Version

## Part 3 of 18

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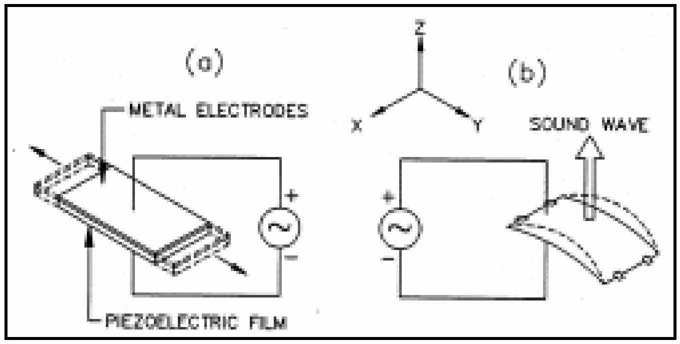
# FREQUENCY RESPONSE

Unlike piezo ceramic transducers, piezo film transducers offer wide dynamic range and are also broadband. These wide band characteristics (near dc to 2GHz) and low Q are partly attributable to the polymers' softness. As audio transmitters, a curved piezo film element, clamped at each end, vibrates in the length ($d_{31}$) mode, as shown in Figure 10. Piezo film is a very high fidelity tweeter, also used in novelty speakers for toys, inflatables and apparel. The $d_{31}$ configuration (Figure 10) is also used for air ultrasound ranging applications up to frequencies of about 50 kHz.

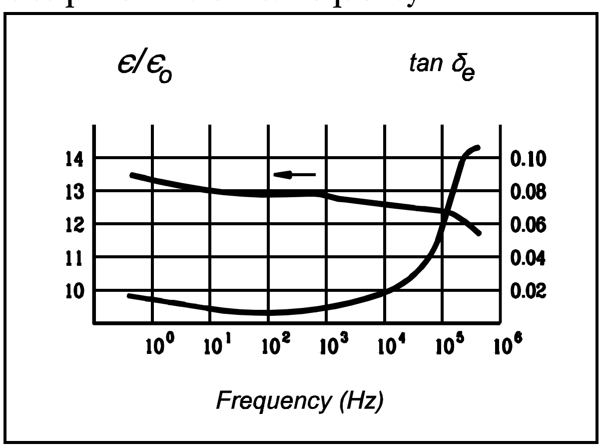
**Figure 10. Clamped film in $d_{31}$ mode produces sound**




When used as a high ultrasonic transmitter (generally >500kHz), piezo film is normally operated in the thickness ($d_{33}$) mode. Maximum transmission occurs at thickness resonance. The basic half-wavelength resonance of 28µm piezo film is about 40 MHZ:

$$f_r = \frac{v}{2t} = \frac{2.2 x 10^3 m/\sec}{2 x 28 \; x 10^{-6} m}$$

**Figure 11. Dielectric permittivity and dissipation factor vs. frequency**




Resonance values thus depend on film thickness. They range from low MHZ for thick films (1,000 $\mu m$) to >100mHz for very thin films.

Figure 11 shows the effect that frequency has on permittivity and dissipation factor at room temperature. As a result of its very low permittivity ε (1 percent that of piezo ceramics), the film exhibits *g*-constants (voltage output coefficients) that are significantly greater than piezo ceramics (g = d/ε).

# PIEZO FILM AT LOW FREQUENCIES

## Introduction

The behavior of a piezo film component at low frequencies is fairly straightforward to describe in electrical terms, yet is quite frequently misunderstood. Since any practical application of the technology will most likely involve some consideration of this topic, it is the intent of this article to examine the subject at some length. The treatment is made as non-mathematical as possible, with verbal descriptions and real-world examples being used to illustrate the concepts. Some familiarity with the use of FFT techniques to transform between time-domain and frequency-domain descriptions is assumed, but not essential.

## Connecting Up

In most instances, the first evaluation of piezo film begins with connecting a piezo component to an oscilloscope via a probe ("scope probe"). Under normal electronics circumstances, a scope probe can be considered to be an "infinite impedance" - so high, that its effect on the circuit under test can be neglected. **Not so with piezo film** - in many cases, a scope probe can act almost like a short-circuit. Typical probes, when plugged in to an oscilloscope, have an effective *resistance* of 1MΩ (one million ohms). Others may be fixed at 10MΩ, while many are conveniently switchable between "x1" ( 1MΩ) and "x10" (10MΩ). Note that the physical element comprising the 1MΩ resistance is usually built into the oscilloscope input stage, rather than being a discrete component within the probe itself. A "x1" probe is thus basically a length of shielded cable with suitable contacts attached to each end.

## Source Capacitance

To analyze what will happen when the probe is connected, we now need to consider the properties of the piezo film element. Perhaps the most important characteristic (after the piezoelectric property, of course) is the material's *capacitance*. Capacitance is a measure of any component's ability to store electrical charge, and is always present when two conductive plates are brought close together. In our case, the conductive plates are the conductive electrodes printed or metallized onto each surface of the film. The capacitance of the device is strongly affected by the properties of the insulator serving to space the plates apart, and the measure of the insulator's capacity to store charge is given by its *dielectric constant* or *permittivity*.

PVDF has a high dielectric constant compared with most polymers, with its value being about 12 (relative to the permittivity of free space).

Obviously, the capacitance of an element will increase as its plate area increases, so a large sheet of film will have a larger capacitance than a small element. Capacitance also increases as the film thickness *decreases*, so for the same surface geometry, a thin film will have a higher capacitance than a thick film.

These factors are formally related in the equation:

$$C = \varepsilon \frac{A}{t}$$

where C is the capacitance of the film,
$\varepsilon$ is the permittivity (which can also be expressed in the form

$\varepsilon = \varepsilon_r \varepsilon_0$ where $\varepsilon_r$ is the relative permittivity (about 12 for PVDF), and $\varepsilon_0$ is the permittivity of free space (a constant, $8.854 \times 10^{-12}$ F/m)

A is the active (overlap) area of the film's electrodes
and= t= is the film thickness

The units of capacitance are Farads (F), but usually much smaller sub-multiples are encountered: microfarads (µF or $10^{-6}$ F), nanofarads (nF or $10^{-9}$ F) and picofarads (pF or $10^{-12}$ F).

**Table 3. Capacitance values of common piezo film components**

| Description | Part No. | Capacitance |
|---|---|---|
| LDT0-028K/L | 0-1002794-1 | 500 pF |
| DT1-028K/L | 1-1002908-0 | 1.3 nF |
| DT1-052K/L | 2-1002908-0 | 650 pF |
| DT2-028K/L | 1-1003744-0 | 2.6 nF |
| DT4-028K/L | 1-1002150-0 | 9 nF |
| 8" x 11" 28 µm | 1-1003702-4 | 30 nF |
| HYD-CYL-100 | 0-1001911-1 | 43 pF |

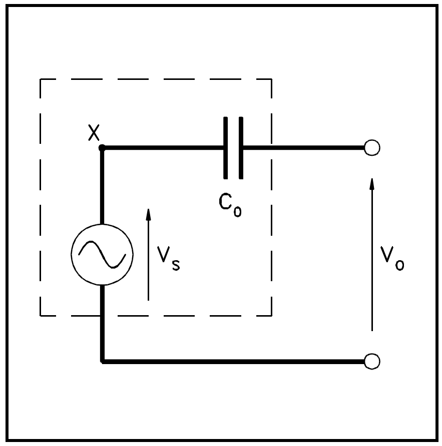
The capacitance of any piezo film element can be calculated using the formula, or measured directly using a hand-held capacitance meter, or bench-top instrument such as an "LCR bridge".

Capacitance values should be quoted at a given measurement frequency - where this is not given, a frequency of 1 kHz is often assumed. Capacitance values of piezo film components usually decrease as the measurement frequency increases.

## Equivalent Circuit of Piezo Film

We are now ready to draw out an electrical equivalent of the piezo film element. There are two equally valid "models" - one is a *voltage* source in series with a capacitance, the other a *charge* generator in parallel with a capacitance - but the latter is uncommon in electrical circuit analysis and we will concentrate on the voltage source (see Figure 12).

**Figure 12. Piezo Film Element as a simple voltage generator**




The dashed line represents the "contents" of the piezo film component. The voltage source $V_S$ is the piezoelectric generator itself, and this source is directly proportional to the applied stimulus (pressure, strain, etc). It is not the purpose of this article to elaborate further on the calculations involved, but it is important to realize that this voltage will absolutely follow the applied stimulus - it is a "perfect" source.

Note, however, that the node marked "X" can never be accessed! The film's capacitance $C_0$ will always be present and connected when we monitor the "output" of the film at the electrodes.

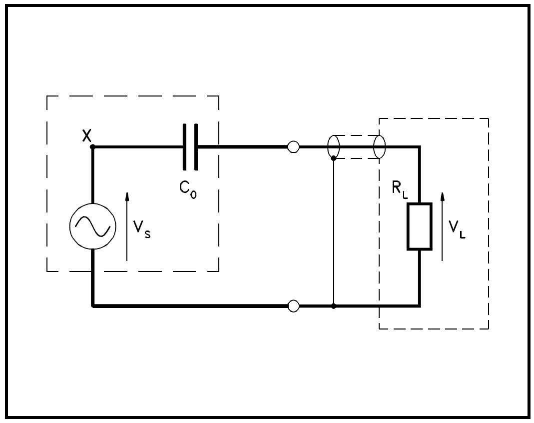
## Adding in a resistive load

Now we can add in the effect of connecting up to the oscilloscope. The oscilloscope and its probe are modeled simply as a pure resistance, although in reality there will be a very small capacitance associated with the probe and the cable (usually in the region of 30 to 50 pF). This can be neglected if the film capacitance is significantly higher in value.

The voltage measured across the load resistor $R_L$ will **not** necessarily be the same voltage developed by the "perfect" source ($V_S$).

To see why, it is helpful to redraw this circuit in another way.

**Figure 13. Adding the oscilloscope as resistive load**




## Potential Divider

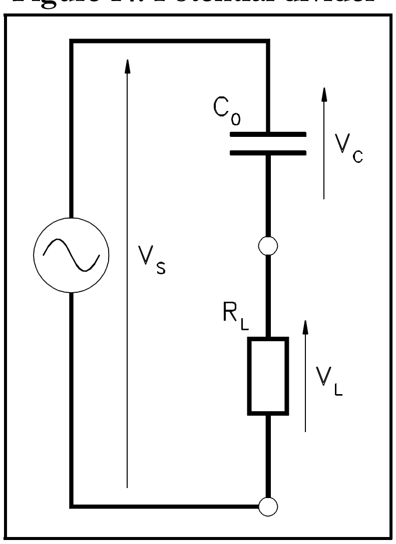
With the circuit shown in Figure 13 redrawn as in Figure 14, it is easier to see why the full source voltage does not always appear across the resistive load.

A *potential divider* is formed by the *series* connection of the capacitance and the resistance. Since the capacitance has an impedance which varies with frequency, the share of the full source voltage which appears across $R_L$ also varies with frequency.

The proportion ($V_L$) of $V_S$ which appears across $R_L$ is given by:

$$V_L = \frac{R_L}{R_L + Z_C}$$

**Figure 14. Potential divider**




where

$$Z_C = -jX_C = -\frac{j}{2\pi fC}$$

(j denoting √-1, and $X_C$ being the reactance of the capacitive element. For simplicity, we ignore any resistive component of the film's impedance).

The above equations may be used in simple ways to calculate the voltage level expected to be observed in simple cases where the frequency of excitation is constant, and so a value of f can simply be substituted. In many real-world cases, however, there may be a distribution of signal energy over a band of frequencies. Then it becomes useful to consider the "frequency response" of the network.

## Frequency Response

This is illustrated in the following example graphs. First, a lin/lin plot is shown (Figure 15, linear y-scale or amplitude, plotted against linear x-scale or frequency) with the corresponding phase plot (Figure 16) also shown in lin/lin form. Following these is a log/log plot (Figure 17), which will be dealt with in a little greater detail.

**Figure 15. Magnitude response of R-C filter**

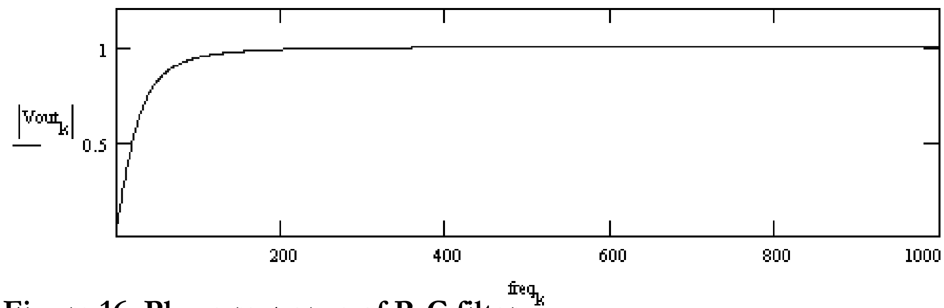
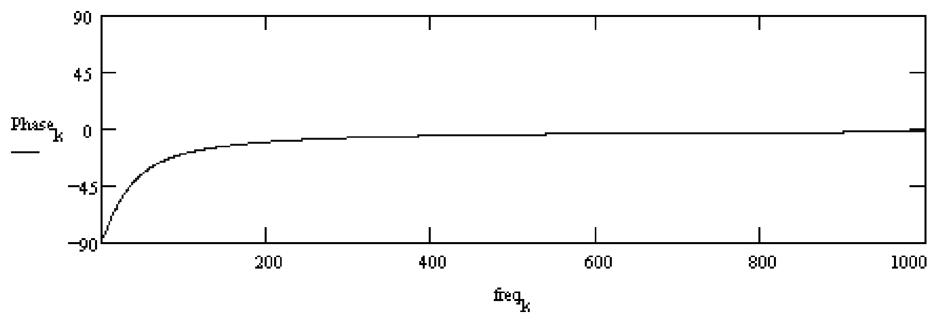
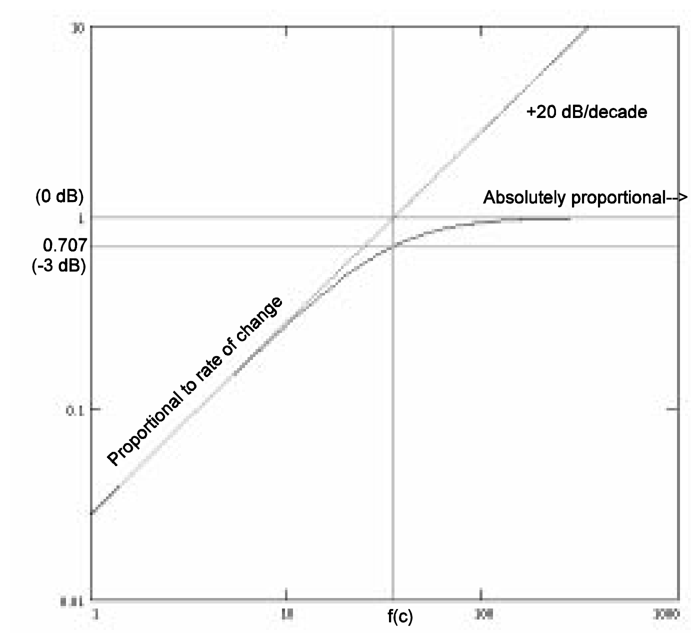



**Figure 16. Phase response of R-C filter**




Note that the phase curve indicates that at very low frequencies, the observed voltage will show significant phase deviation from the source (limiting at -90° or -π/2 radians at "DC" or zero Hz). The significance of this effect is great if the piezo film element is to be used as part of a control loop.

**Figure 17. Magnitude response shown as log/log plot**



## Analysis of the log/log R-C frequency response curve

Some key features:

- the overall characteristic of this network is known as a high-pass filter
- the frequency at which the magnitude falls to 0.707 or -3 dB is known as the "cut-off" or "corner" frequency of the high-pass filter
- this frequency can be calculated as $f(c) = 1/(2\pi RC)$, when both the resistance R and capacitance C are known
- at frequencies well *below* the cut-off frequency, the plot has the form of a straight line with gradient +20 dB/decade (in other words, doubling the frequency will double the signal amplitude) - this characteristic is identical with that of a *differentiator* network, and gives an output which is proportional to the *rate of change* of the input quantity
- at frequencies well *above* the cut-off frequency, the plot is level at "unity gain" and the output is directly proportional to the input quantity
- the filter characteristic can be approximated by these two intersecting straight lines, but the magnitude actually follows an asymptotic curve, with magnitude -3 dB at the cut-off frequency where the straight lines cross
- the filter characteristic can then be applied to the frequency-domain description of any practical signal by multiplying the filter transfer characteristic with the spectrum of the input signal, and deriving a response curve (output) which can in turn be transformed back into a time-domain signal.

Some practical examples of the effect of this filter characteristic will be shown next. For each signal, the time-domain description of the "perfect source" (e.g. the waveform which would be seen on an oscilloscope if the filter characteristic was absent) is given first, followed by its spectrum (obtained by use of the FFT [Fast Fourier Transform] algorithm supplied in the analysis software), then the filter characteristic (identical for all examples, but shown to emphasize the effect), then the resulting output signal spectrum obtained by multiplying the complex input spectrum by the complex filter characteristic, and finally the corresponding time-domain description obtained by inverse FFT, which shows the waveform an engineer would expect to observe in reality.

**Note:** in Figures 15, 16 and 17 the R-C values used to generate the curve were R = 1MΩ and C = 4.5 nF. In the following plots, the value of C was reduced to 1.5 nF. These values were chosen somewhat arbitrarily to demonstrate the principle, and so the scaling on the curves has not been annotated. But the time waveforms can be read in x units of seconds, and the frequency curves with x units of Hz. The cut-off frequency for R = 1MΩ and C = 1.5 nF is approximately 106 Hz.

## Key to following figures

**Figure 18** shows a relatively high-frequency sine wave passing through the network. In the input spectrum, the signal is represented by a single spectral line at the appropriate frequency. This frequency is just below the filter "cut-off", and so is only slightly attenuated by the network. The resulting output wave is diminished in amplitude, and slightly shifted in phase.

**Figure 19** shows the same process applied to a slower sine wave. In this case, the attenuation is much greater, and the phase shift more significant. This situation occurs when trying to monitor steady vibration at "too low" a frequency using a piezo sensor. The phase behavior may be significant if a control loop is to be implemented.

**Figure 20** shows a harmonic series, with a number of discrete spectral lines all lying below the cut-off frequency. Each is attenuated to a different extent, and so the "balance" of harmonics in the output signal is altered.

**Figure 21** shows a slow half-sine input pulse (typical of many mechanical impact signals). Although the high-frequency content is largely unaltered, the output waveform appears heavily "distorted" and clearly shows both positive and negative excursions, whereas the input waveform is unipolar.

**Figure 22** shows a sawtooth waveform with slowly rising "leading edge" followed by a "snap" descent back to zero. Many piezo switches detect this form of mechanical event. In the output waveform, the "leading edge" has almost disappeared, but the "snap" gives almost full amplitude. Note the polarity of the output pulse relative to the input waveform.

**Figure 18. Effect of R-C filter on High Frequency Sine Wave input waveform**

a) Input waveform

b) Input spectrum

c) Filter characteristic

d) Output spectrum

e) Output waveform

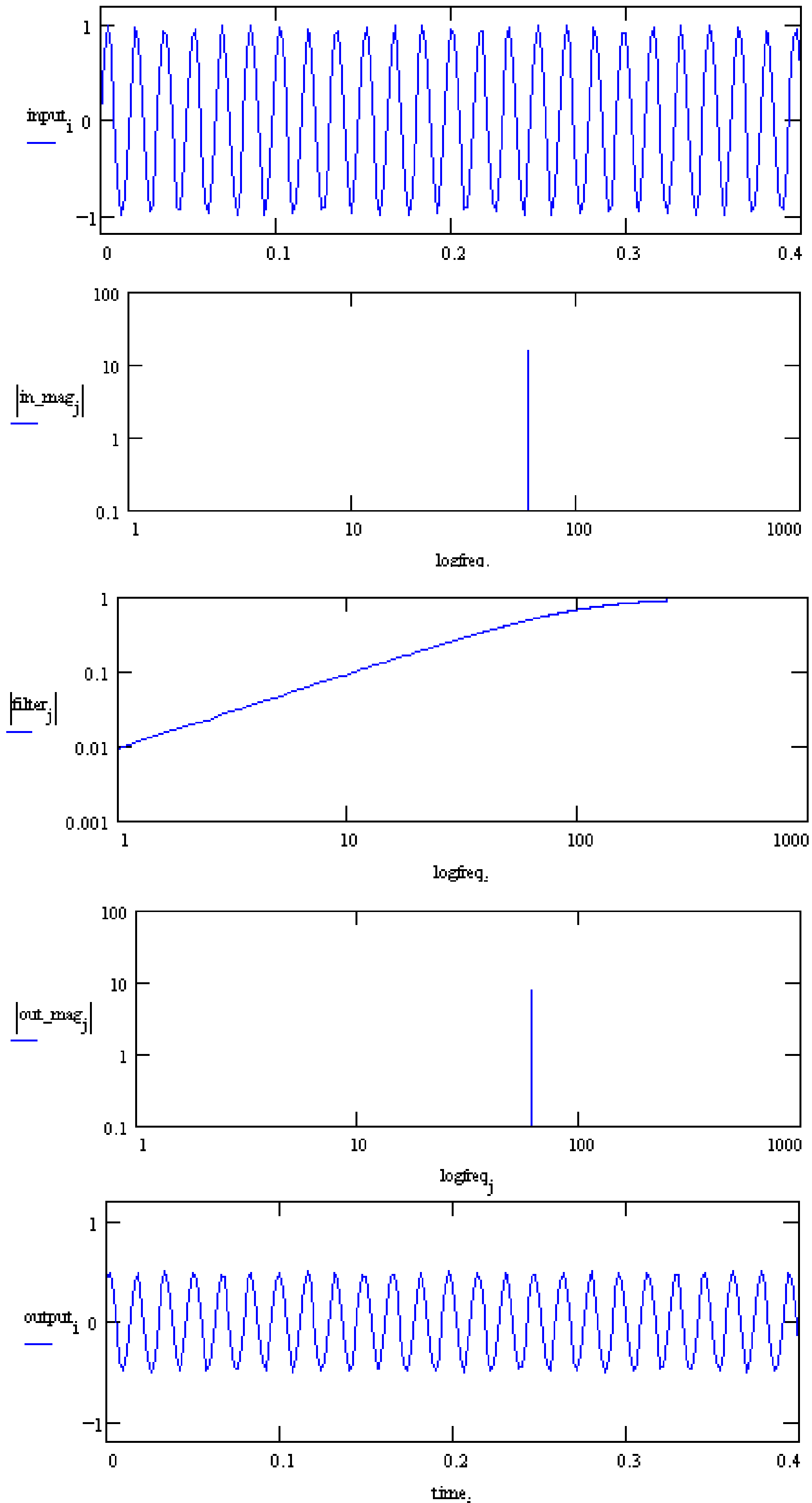
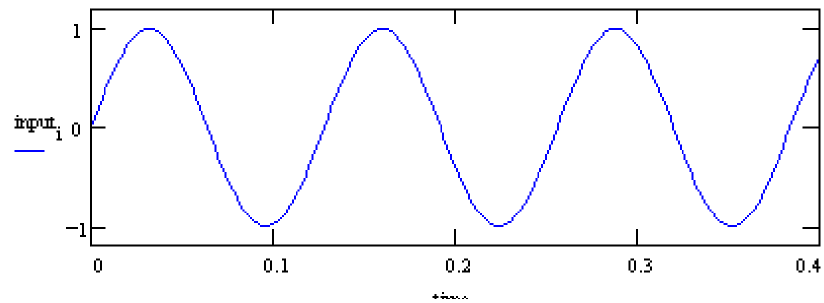
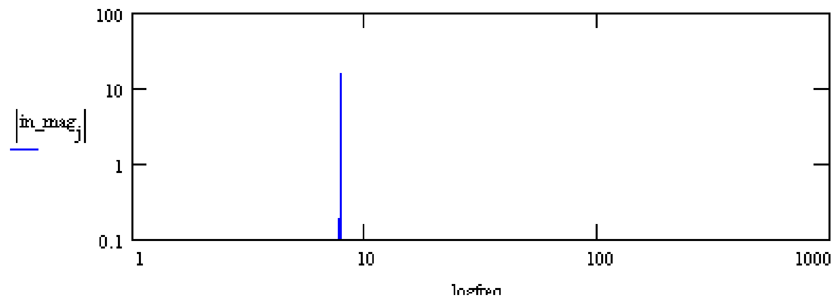


**Figure 19. Effect of R-C filter on Low Frequency Sine Wave input waveform**

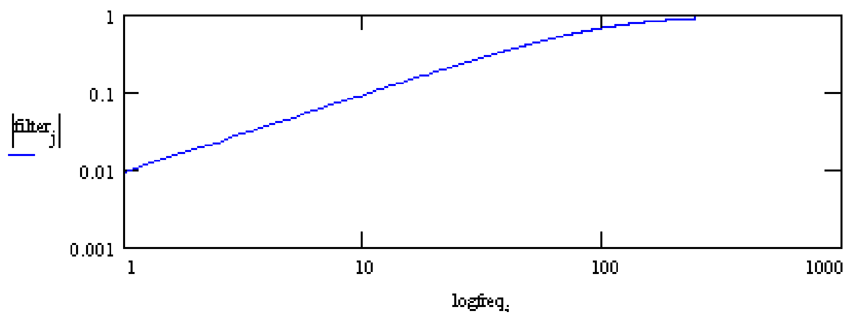
a) Input waveform



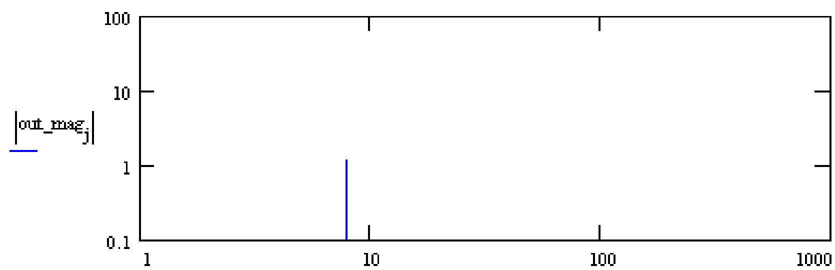

b) Input spectrum




c) Filter characteristic




d) Output spectrum




e) Output waveform

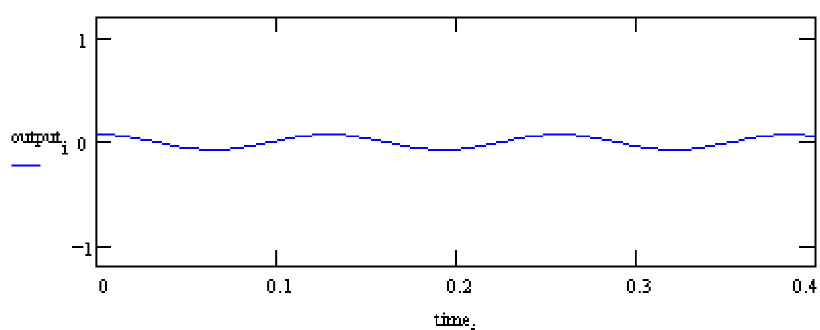


**Figure 20. Effect of R-C filter on Harmonic Series input waveform**

a) Input waveform

b) Input spectrum

c) Filter characteristic

d) Output spectrum

e) Output waveform

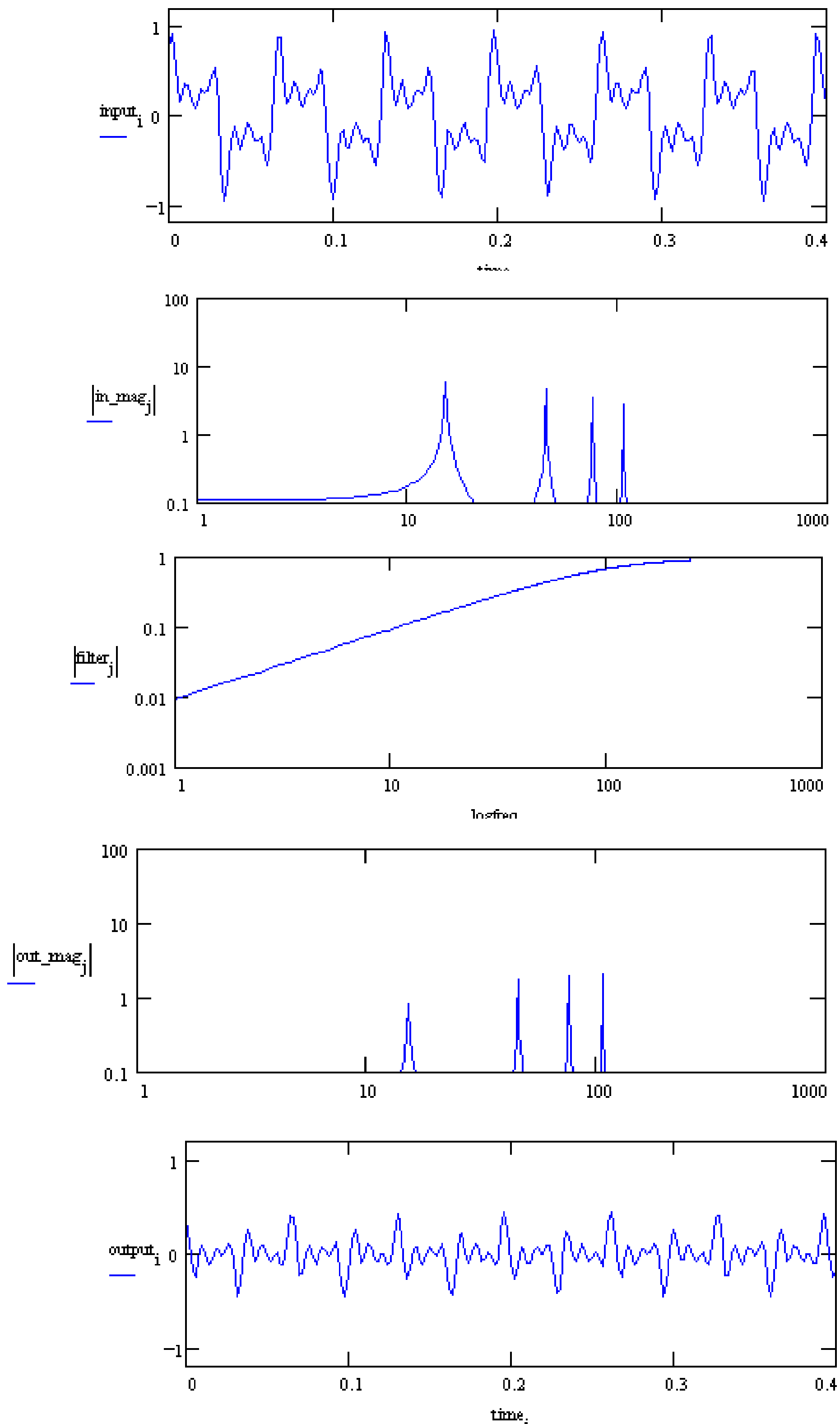


**Figure 21. Effect of R-C filter on Slow Half-Sine Transient input waveform**

a) Input waveform

b) Input spectrum

c) Filter characteristic

d) Output spectrum

e) Output waveform

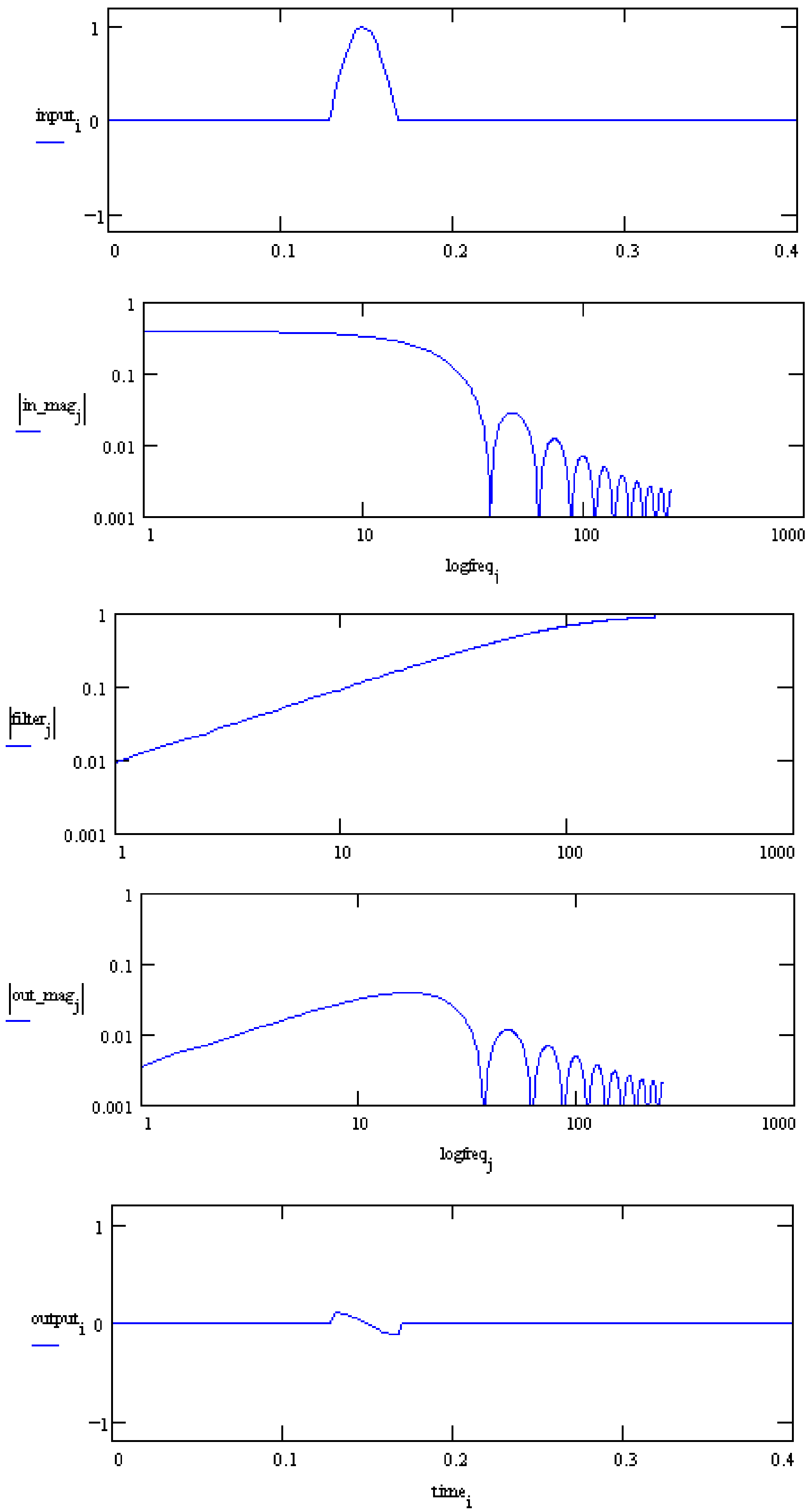
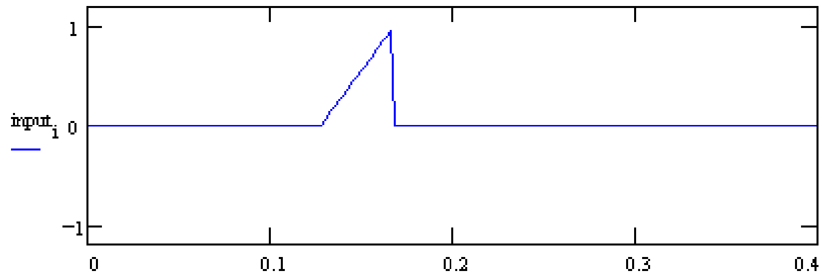
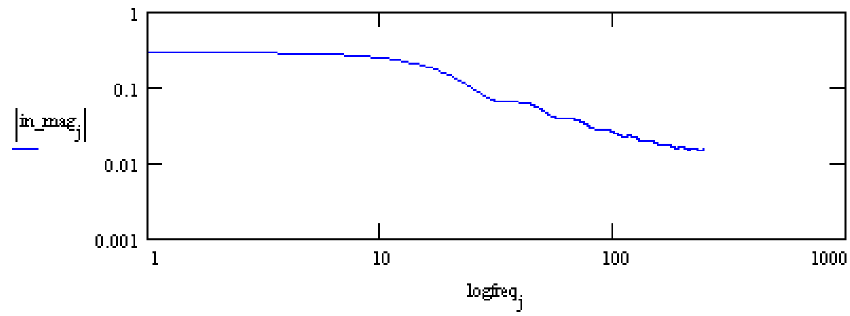


**Figure 22. Effect of R-C filter on Slow Sawtooth Transient input waveform**

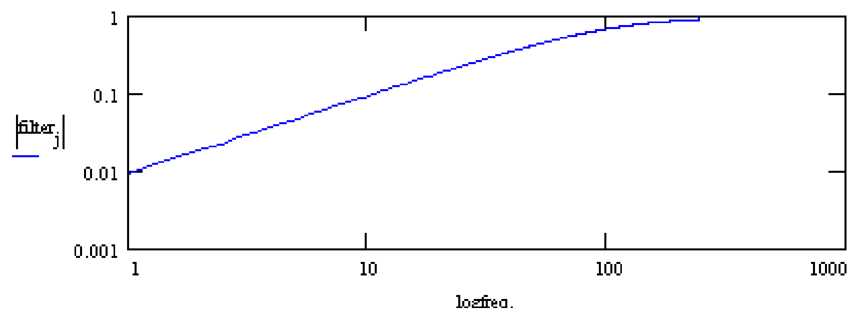
a) Input waveform



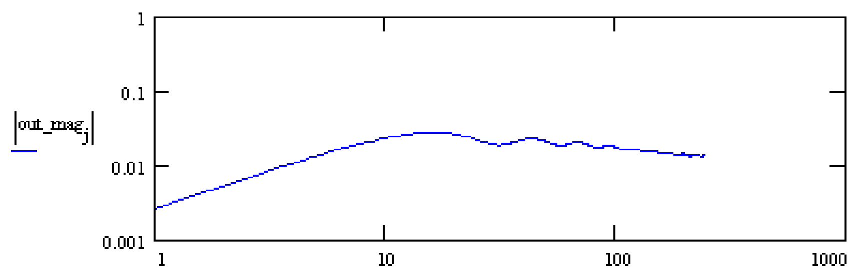

b) Input spectrum




c) Filter characteristic




d) Output spectrum




e) Output waveform