

## SDOF linear oscillator

### Response to Periodic and Non-periodic Loadings

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## Outline

Response to Periodic Loading

Fourier Transform

The Discrete Fourier Transform

Response to General Dynamic Loadings

Undamped SDOF systems

Damped SDOF systems

Relationship between time and frequency domain

## Response

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## Response to Periodic Loading

### Response to Periodic Loading

Introduction

Fourier Series Representation

Fourier Series of the Response

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The Discrete Fourier Transform

Response to General Dynamic Loadings

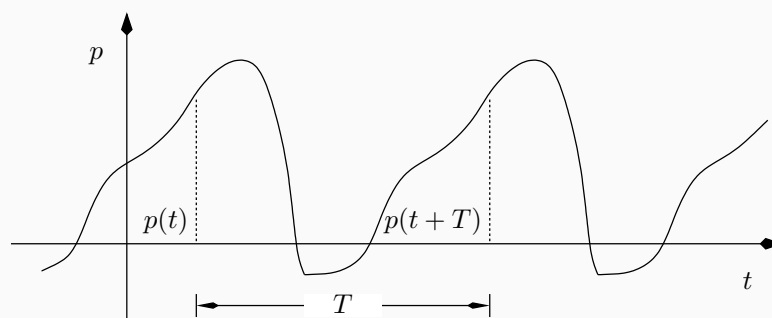
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## Introduction

A periodic loading is characterized by the identity

$$p(t) = p(t + T)$$

where  $T$  is the *period* of the loading, and  $\omega_1 = \frac{2\pi}{T}$  is its *principal frequency*.



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## Introduction

Fourier theorem asserts that periodic loadings can be represented by an infinite series of harmonic functions. E.g., for an antisymmetric periodic loading of period  $T$  we have a series composed of antisymmetric harmonic functions

$$p(t) = p(-t) = \sum_{j=1}^{\infty} p_j \sin j\omega_1 t = \sum_{j=1}^{\infty} p_j \sin \omega_j t \quad (\text{with } \omega_j = j \frac{2\pi}{T}).$$

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## Introduction

The **steady-state response** of a SDOF system for a harmonic loading

$\Delta p_j(t) = p_j \sin \omega_j t$  is known; with  $\beta_j = \omega_j / \omega_n$  the s-s response is:

$$x_{j,s-s} = \frac{p_j}{k} D(\beta_j, \zeta) \sin(\omega_j t - \theta(\beta_j, \zeta)) = a_j \cos \omega_j t + b_j \sin \omega_j t.$$

The response to an individual harmonic component can be interpreted as a term of another different Fourier series, that possibly represents the **steady-state response** of the dynamic system to  $p(t)$ .

It can be shown that, under very wide assumptions, the infinite series whose terms are the s-s responses to the harmonic components of  $p(t)$  is indeed the Fourier series representation of the SDOF **steady-state response** to  $p(t)$ .

## Introduction

*Due to the asymptotic behaviour of  $D(\beta; \zeta)$  ( $D$  goes to zero as  $\beta^{-2}$  for  $\beta \gg 1$ ) it is apparent that a good approximation to the steady-state response can be obtained using a limited number of low-frequency terms.*

## Fourier Series

Using Fourier theorem any *practical* periodic loading can be expressed as a series of harmonic loading terms.

We can represent a loading  $p(t)$ , of period  $T_p$ , using its Fourier series expansion

$$p(t) = \sum_{j=0}^{\infty} a_j \cos \omega_j t + \sum_{j=0}^{\infty} b_j \sin \omega_j t, \quad \omega_j = j \omega_1 = j \frac{2\pi}{T_p}.$$

Considering the orthogonality relationship over the period  $T_p$ ,

$$\int_0^{T_p} \cos \omega_i t \cos \omega_j t dt = \int_0^{T_p} \sin \omega_i t \sin \omega_j t dt = \delta_{ij} \frac{T_p}{2}, \quad \int_0^{T_p} \cos \omega_i t \sin \omega_j t dt = 0, \quad i, j = 0, \dots,$$

the amplitudes of the harmonic components are

$$a_0 = \frac{1}{T_p} \int_0^{T_p} p(t) dt, \quad a_j = \frac{2}{T_p} \int_0^{T_p} p(t) \cos \omega_j t dt, \quad b_0 = 0 \quad b_j = \frac{2}{T_p} \int_0^{T_p} p(t) \sin \omega_j t dt.$$

Note that the case  $i = j = 0$  is a special case...

## Fourier Coefficients

If  $p(t)$  has not an analytical representation and must be measured experimentally or computed numerically, we may assume that it is possible

- (a) to divide the period in  $N$  equal parts  $\Delta t = T_p/N$ ,
- (b) measure or compute  $p(t)$  at a discrete set of instants  $t_1, t_2, \dots, t_N$ , with  $t_m = m\Delta t$ ,

obtaining a discrete set of values  $p_m$ ,  $m = 1, \dots, N$  (note that  $p_0 = p_N$  by periodicity).

Under these assumptions the, e.g., cosine-wave amplitude coefficients can be approximated using the trapezoidal rule of integration (note that  $p_0 = p_N$  and

$$a_j \approx \frac{2\Delta t}{T_p} \sum_{m=1}^N p_m \cos \omega_j t_m = \frac{2}{N} \sum_{m=1}^N p_m \cos(j\omega_1 m\Delta t) = \frac{2}{N} \sum_{m=1}^N p_m \cos \frac{j m 2\pi}{N}.$$

## Periodicity

The coefficients of the Discrete Fourier Series are periodic, with period  $N$ .

E.g., here it is how we can compute  $a_{j+N}$  according to its definition:

$$\begin{aligned} a_{j+N} &= \frac{2}{N} \sum_{m=1}^N p_m \cos \frac{2(j+N)m\pi}{N} = \frac{2}{N} \sum_{m=1}^N p_m \cos \frac{2(jm + Nm)\pi}{N} \\ &= \frac{2}{N} \sum_{m=1}^N p_m \cos \left( \frac{2jm\pi}{N} + 2m\pi \right) = \frac{2}{N} \sum_{m=1}^N p_m \cos \frac{2jm\pi}{N} = a_j \end{aligned}$$

## Exponential Form

The Fourier series can also be written in terms of exponentials of imaginary argument,

$$p(t) = \sum_{j=-\infty}^{\infty} P_j \exp i\omega_j t$$

where the complex amplitude coefficients are given by

$$P_j = \frac{1}{T_p} \int_0^{T_p} p(t) \exp -i\omega_j t \, dt, \quad j = -\infty, \dots, +\infty.$$

For a sampled  $p_m$  we can write, using the trapezoidal integration rule and substituting  $t_m = m\Delta t = m T_p/N$ ,  $\omega_j = j 2\pi/T_p$ :

$$P_j \approx \frac{1}{N} \sum_{m=1}^N p_m \exp(-i \frac{2\pi j m}{N}).$$

For sampled input also the coefficients of the exponential series are periodic,  $P_{j+N} = P_j$ .

## Undamped Response

We have seen that the steady-state response to the  $j$ th sine-wave harmonic can be written as

$$x_j = \frac{b_j}{k} \left[ \frac{1}{1 - \beta_j^2} \right] \sin \omega_j t, \quad \beta_j = \omega_j / \omega_n,$$

analogously, for the  $j$ th cosine-wave harmonic,

$$x_j = \frac{a_j}{k} \left[ \frac{1}{1 - \beta_j^2} \right] \cos \omega_j t.$$

Finally, we write

$$x(t) = \frac{1}{k} \left\{ a_0 + \sum_{j=1}^{\infty} \left[ \frac{1}{1 - \beta_j^2} \right] (a_j \cos \omega_j t + b_j \sin \omega_j t) \right\}.$$

## Damped Response

In the case of a damped oscillator, we must substitute the steady state response for both the  $j$ th sine- and cosine-wave harmonic,

$$x(t) = \frac{a_0}{k} + \frac{1}{k} \sum_{j=1}^{\infty} \frac{+(1 - \beta_j^2) a_j - 2\zeta\beta_j b_j}{(1 - \beta_j^2)^2 + (2\zeta\beta_j)^2} \cos \omega_j t + \frac{1}{k} \sum_{j=1}^{\infty} \frac{+2\zeta\beta_j a_j + (1 - \beta_j^2) b_j}{(1 - \beta_j^2)^2 + (2\zeta\beta_j)^2} \sin \omega_j t.$$

As usual, the exponential notation is neater,

$$x(t) = \sum_{j=-\infty}^{\infty} \frac{P_j}{k} \frac{\exp i\omega_j t}{(1 - \beta_j^2) + i(2\zeta\beta_j)}.$$

## Example

As an example, consider the loading  $p(t) = \max\{p_0 \sin \frac{2\pi t}{T_p}, 0\}$

$$a_0 = \frac{1}{T_p} \int_0^{T_p/2} p_0 \sin \frac{2\pi t}{T_p} dt = \frac{p_0}{\pi},$$

$$a_j = \frac{2}{T_p} \int_0^{T_p/2} p_0 \sin \frac{2\pi t}{T_p} \cos \frac{2\pi j t}{T_p} dt = \begin{cases} 0 & \text{for } j \text{ odd} \\ \frac{p_0}{\pi} \left[ \frac{2}{1-j^2} \right] & \text{for } j \text{ even,} \end{cases}$$

$$b_j = \frac{2}{T_p} \int_0^{T_p/2} p_0 \sin \frac{2\pi t}{T_p} \sin \frac{2\pi j t}{T_p} dt = \begin{cases} \frac{p_0}{2} & \text{for } j = 1 \\ 0 & \text{for } n > 1. \end{cases}$$

### Example cont.

Assuming  $\beta_1 = 3/4$ , from  $p = \frac{p_0}{\pi} \left( 1 + \frac{\pi}{2} \sin \omega_1 t - \frac{2}{3} \cos 2\omega_1 t - \frac{2}{15} \cos 4\omega_1 t - \dots \right)$  with the dynamic amplification factors

$$D_1 = \frac{1}{1 - (1\frac{3}{4})^2} = \frac{16}{7}, \quad D_2 = \frac{1}{1 - (2\frac{3}{4})^2} = -\frac{4}{5}, \quad D_4 = \frac{1}{1 - (4\frac{3}{4})^2} = -\frac{1}{8}, \quad D_6 = \dots$$

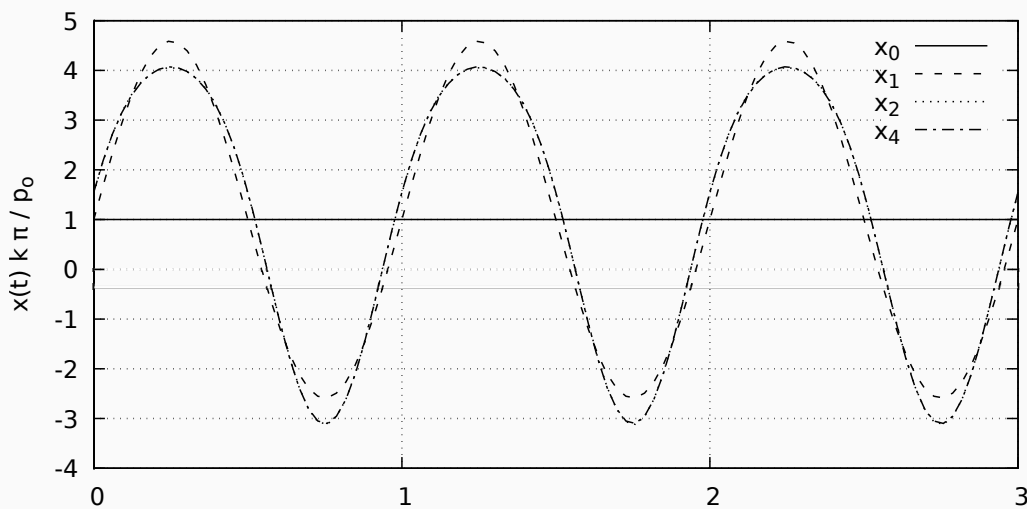
etc, we have

$$x(t) = \frac{p_0}{k\pi} \left( 1 + \frac{8\pi}{7} \sin \omega_1 t + \frac{8}{15} \cos 2\omega_1 t + \frac{1}{60} \cos 4\omega_1 t + \dots \right)$$

Take note, **these solutions are particular solutions!** If your solution has to respect given initial conditions, you must consider also the homogeneous solution.

### Example cont.

$$x_i = \sum_{j=1, \dots, i} a_j \cos \omega_j t + b_j \sin \omega_j t$$



## Fourier Transform

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## Outline of Fourier transform

Response to Periodic Loading

Fourier Transform

Extension of Fourier Series to non periodic functions

Response in the Frequency Domain

The Discrete Fourier Transform

Response to General Dynamic Loadings

Undamped SDOF systems

Damped SDOF systems

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## Non periodic loadings

It is possible to extend the Fourier analysis to non periodic loading. Let's start from the Fourier series representation of the load  $p(t)$ ,

$$p(t) = \sum_{-\infty}^{+\infty} P_r \exp(i\omega_r t), \quad \omega_r = r\Delta\omega, \quad \Delta\omega = \frac{2\pi}{T_p},$$

introducing  $P(i\omega_r) = P_r T_p$  and substituting,

$$p(t) = \frac{1}{T_p} \sum_{-\infty}^{+\infty} P(i\omega_r) \exp(i\omega_r t) = \frac{\Delta\omega}{2\pi} \sum_{-\infty}^{+\infty} P(i\omega_r) \exp(i\omega_r t).$$

Due to periodicity, we can modify the extremes of integration in the expression for the complex amplitudes,

$$P(i\omega_r) = \int_{-T_p/2}^{+T_p/2} p(t) \exp(-i\omega_r t) dt.$$

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## Non periodic loadings (2)

If the loading period is extended to infinity to represent the non-periodicity of the loading ( $T_p \rightarrow \infty$ ) then (a) the frequency increment becomes infinitesimal ( $\Delta\omega = \frac{2\pi}{T_p} \rightarrow d\omega$ ) and (b) the discrete frequency  $\omega_r$  becomes a continuous variable,  $\omega$ .

In the limit, for  $T_p \rightarrow \infty$  we can then write

$$p(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} P(i\omega) \exp(i\omega t) d\omega$$
$$P(i\omega) = \int_{-\infty}^{+\infty} p(t) \exp(-i\omega t) dt,$$

which are known as the inverse and the direct Fourier Transforms, respectively, and are collectively known as the Fourier transform pair.

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## SDOF Response

In analogy to what we have seen for periodic loads, the response of a damped SDOF system can be written in terms of  $H(i\omega)$ , the complex frequency response function,

$$x(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} H(i\omega) P(i\omega) \exp i\omega t dt, \quad \text{where}$$

$$H(i\omega) = \frac{1}{k} \left[ \frac{1}{(1 - \beta^2) + i(2\zeta\beta)} \right] = \frac{1}{k} \left[ \frac{(1 - \beta^2) - i(2\zeta\beta)}{(1 - \beta^2)^2 + (2\zeta\beta)^2} \right], \quad \beta = \frac{\omega}{\omega_n}.$$

To obtain the response *through frequency domain*, you should evaluate the above integral, but analytical integration is not always possible, and when it is possible, it is usually very difficult, implying contour integration in the complex plane (for an example, see Example **E6-3** in Clough Penzien).

## The DFT

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## Outline of the Discrete Fourier Transform

Response to Periodic Loading

Fourier Transform

The Discrete Fourier Transform

The Discrete Fourier Transform

Aliasing

The Fast Fourier Transform

Response to General Dynamic Loadings

Undamped SDOF systems



## Discrete Fourier Transform

To overcome the analytical difficulties associated with the inverse Fourier transform, one can use appropriate numerical methods, leading to good approximations.

Consider a loading of finite period  $T_p$ , divided into  $N$  equal intervals  $\Delta t = T_p/N$ , and the set of values  $p_s = p(t_s) = p(s\Delta t)$ .

We can approximate the complex amplitude coefficients with a sum,

$$P_r = \frac{1}{T_p} \int_0^{T_p} p(t) \exp(-i\omega_r t) dt, \quad \text{that, by trapezoidal rule, is}$$

$$\cong \frac{1}{N\Delta t} \left( \Delta t \sum_{s=0}^{N-1} p_s \exp(-i\omega_r t_s) \right) = \frac{1}{N} \sum_{s=0}^{N-1} p_s \exp(-i\frac{2\pi r s}{N}).$$

## Discrete Fourier Transform (2)

In the last two passages we have used the relations

$$p_N = p_0, \quad \exp(i\omega_r t_N) = \exp(ir\Delta\omega T_p) = \exp(ir2\pi) = \exp(i0)$$

$$\omega_r t_s = r\Delta\omega s\Delta t = r s \frac{2\pi T_p}{T_p N} = \frac{2\pi r s}{N}.$$

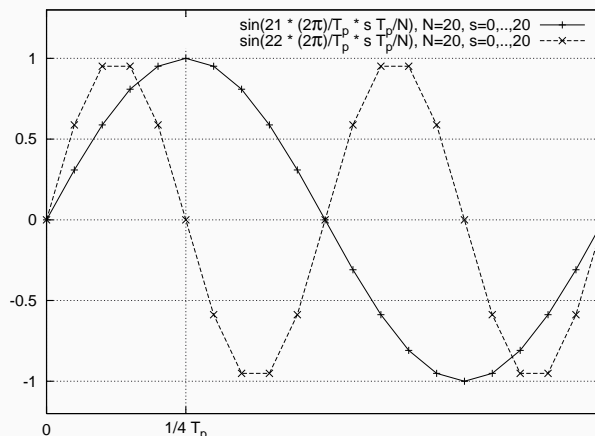
Take note that the discrete function  $\exp(-i\frac{2\pi r s}{N})$ , defined for integer  $r, s$  is periodic with period  $N$ , implying that the complex amplitude coefficients are themselves periodic with period  $N$ .

$$P_{r+N} = P_r$$

Starting in the time domain with  $N$  distinct complex numbers,  $p_s$ , we have found that in the frequency domain our load is described by  $N$  distinct complex numbers,  $P_r$ , so that we can say that our function is described by the same amount of information in both domains.

## Aliasing

Only  $N/2$  distinct frequencies ( $\sum_0^{N-1} = \sum_{-N/2}^{+N/2}$ ) contribute to the load representation, what if the frequency content of the loading has contributions from frequencies higher than  $\omega_{N/2}$ ? What happens is *aliasing*, i.e., the upper frequencies contributions are mapped to contributions of lesser frequency.



See the plot above: the contributions from the high frequency sines, when sampled, are indistinguishable from the contributions from lower frequency components, i.e., are *aliased* to lower frequencies!

## Aliasing (2)

- The maximum frequency that can be described in the DFT is called the Nyquist frequency,  $\omega_{Ny} = \frac{1}{2} \frac{2\pi}{\Delta t}$ .
- It is usual in signal analysis to remove the signal's higher frequency components preprocessing the signal with a *filter* or a *digital filter*.
- It is worth noting that the *resolution* of the DFT in the frequency domain for a given sampling rate is proportional to the number of samples, i.e., to the duration of the sample.

## The Fast Fourier Transform

The operation count in a DFT is in the order of  $N^2$ .

A Fast Fourier Transform is an algorithm that reduces the number of arithmetic operations needed to compute a DFT.

The first and simpler FFT algorithm is the *Decimation in Time* algorithm by Cooley and Tukey (1965).

The algorithm introduced by Cooley and Tukey is quite complex because it allows to proceed without additional memory, we will describe a different algorithm, that is based on the same principles but requires additional memory and it's rather simpler than the original one.

## Decimation in Time DFT

For simplicity, assume that  $N$  is even and split the DFT summation in two separate sums, with even and odd indices

$$\begin{aligned} X_r &= \sum_{s=0}^{N-1} x_s e^{-\frac{2\pi i}{N} sr}, \quad r = 0, \dots, N-1 \\ &= \sum_{q=0}^{N/2-1} x_{2q} e^{-\frac{2\pi i}{N} (2q)r} + \sum_{q=0}^{N/2-1} x_{2q+1} e^{-\frac{2\pi i}{N} (2q+1)r}. \end{aligned}$$

Collecting  $e^{-\frac{2\pi i}{N} r}$  in the second term and letting  $\frac{2q}{N} = \frac{q}{N/2}$ , we have

$$X_r = \sum_{q=0}^{N/2-1} x_{2q} e^{-\frac{2\pi i}{N/2} qr} + e^{-\frac{2\pi i}{N} r} \sum_{q=0}^{N/2-1} x_{2q+1} e^{-\frac{2\pi i}{N/2} qr},$$

i.e., we have two DFT's of length  $N/2$ . The operations count is just  $2(N/2)^2 = N^2/2$ , but we have to combine these two halves in the full DFT.

## Decimation in Time DFT

Say that

$$X_r = E_r + e^{-\frac{2\pi i}{N}r} O_r$$

where  $E_r$  and  $O_r$  are the even and odd half-DFT's, of which we computed only coefficients from 0 to  $N/2 - 1$ .

To get the full sequence we have to note that

1. the  $E$  and  $O$  DFT's are periodic with period  $N/2$ , and
2.  $\exp(-2\pi i(r + N/2)/N) = e^{-\pi i} \exp(-2\pi ir/N) = -\exp(-2\pi ir/N)$ ,

so that we can write

$$X_r = \begin{cases} E_r + \exp(-2\pi ir/N) O_r & \text{if } r < N/2, \\ E_{r-N/2} - \exp(-2\pi ir/N) O_{r-N/2} & \text{if } r \geq N/2. \end{cases}$$

The algorithm that was outlined can be applied to the computation of each of the half-DFT's when  $N/2$  were even, so that the operation count goes to  $N^2/4$ . If  $N/4$  were even ...

## Pseudocode for CT algorithm

```
def fft2(X, N):
    if N = 1 then
        Y = X
    else
        Y0 = fft2(X0, N/2)
        Y1 = fft2(X1, N/2)
        for k = 0 to N/2-1
            Y_k          = Y0_k + exp(2 pi i k/N) Y1_k
            Y_(k+N/2) = Y0_k - exp(2 pi i k/N) Y1_k
        endfor
    endif
    return Y
```

```
from cmath import exp, pi

def d_fft(x,n):
    """Direct fft of x, a list of n=2**m complex values"""
    return _fft(x,n,[exp(-2*pi*1j*k/n) for k in range(n/2)])

def i_fft(x,n):
    """Inverse fft of x, a list of n=2**m complex values"""
    transform = _fft(x,n,[exp(+2*pi*1j*k/n) for k in range(n/2)])
    return [x/n for x in transform]
```

```

def _fft(x, n, tw):
    """Decimation in Time FFT, to be called by d_fft and i_fft.
    x is the signal to transform, a list of complex values
    n is its length, results are undefined if n is not a power of 2
    tw is a list of twiddle factors, precomputed by the caller

    returns a list of complex values, not normalized if inverse transform"""

    if n == 1: return x # bottom reached, DFT of a length 1 vec x is x

    # call fft with the even and the odd coefficients in x
    # the results are the so called even and odd DFT's
    e, o = _fft(x[0::2], n/2, tw[::2]), _fft(x[1::2], n/2, tw[::2])

    # assemble the partial results:
    # 1st half of full DFT is put in even DFT, 2nd half in odd DFT
    for k in range(n/2):
        e[k], o[k] = e[k]+tw[k]*o[k], e[k]-tw[k]*o[k]

    # concatenate the two halves of the DFT and return to caller
    return e + o

```

If we strip all comments, our FFT function becomes

```

def _fft(x, n, tw):
    if n==1: return x
    e,o=_fft(x[0::2],n/2,tw[::2]),_fft(x[1::2],n/2,tw[::2])
    for k in range(n/2):e[k],o[k]=e[k]+tw[k]*o[k],e[k]-tw[k]*o[k]
    return e+o

```

## Dynamic Response (1)

To evaluate the dynamic response of a linear SDOF system in the frequency domain, use the inverse DFT,

$$x_s = \sum_{r=0}^{N-1} V_r \exp(i \frac{2\pi r s}{N}), \quad s = 0, 1, \dots, N-1$$

where  $V_r = H_r P_r$ .  $P_r$  are the discrete complex amplitude coefficients computed using the direct DFT, and  $H_r$  is the discretization of the complex frequency response function, that for viscous damping is

$$H_r = \frac{1}{k} \left[ \frac{1}{(1 - \beta_r^2) + i(2\zeta\beta_r)} \right] = \frac{1}{k} \left[ \frac{(1 - \beta_r^2) - i(2\zeta\beta_r)}{(1 - \beta_r^2)^2 + (2\zeta\beta_r)^2} \right], \quad \beta_r = \frac{\omega_r}{\omega_n}$$

while for hysteretic damping it is

$$H_r = \frac{1}{k} \left[ \frac{1}{(1 - \beta_r^2) + i(2\zeta)} \right] = \frac{1}{k} \left[ \frac{(1 - \beta_r^2) - i(2\zeta)}{(1 - \beta_r^2)^2 + (2\zeta)^2} \right]$$

## Dynamic Response (2)

Some word of caution...

If you're going to approach the application of the complex frequency response function without proper concern, you're likely to be hurt.

Let's say  $\Delta\omega = 1.0$ ,  $N = 32$ ,  $\omega_n = 3.5$  and  $r = 30$ , what do you think it is the value of  $\beta_{30}$ ? If you are thinking  $\beta_{30} = 30 \Delta\omega / \omega_n = 30/3.5 \approx 8.57$  you're wrong!

Due to aliasing,  $\omega_r = \begin{cases} r\Delta\omega & r \leq N/2 \\ (r - N)\Delta\omega & r > N/2 \end{cases}$ ,

note that in the upper part of the DFT the coefficients correspond to negative frequencies and, staying within our example, it is  $\beta_{30} = (30 - 32) \times 1/3.5 \approx -0.571$ .

If  $N$  is even,  $P_{N/2}$  is the coefficient corresponding to the Nyquist frequency, if  $N$  is odd  $P_{\frac{N-1}{2}}$  corresponds to the largest positive frequency, while  $P_{\frac{N+1}{2}}$  corresponds to the largest negative frequency.

## General Load

## Response to General Dynamic Loading

Response to Periodic Loading

Fourier Transform

The Discrete Fourier Transform

Response to General Dynamic Loadings

Response to infinitesimal impulse

Duhamel Integral

Numerical integration of Duhamel integral

Undamped SDOF systems

## Response to a short duration load

An approximate procedure to evaluate the maximum displacement for a short impulse loading is based on the impulse-momentum relationship,

$$m\Delta\dot{x} = \int_0^{t_0} [p(t) - kx(t)] dt.$$

When one notes that, for small  $t_0$ , the displacement is of the order of  $t_0^2$  while the velocity is in the order of  $t_0$ , it is apparent that the  $kx$  term may be dropped from the above expression, i.e.,

$$m\Delta\dot{x} \approx \int_0^{t_0} p(t) dt.$$

## Response to a short duration load

Using the previous approximation, the velocity at time  $t_0$  is

$$\dot{x}(t_0) = \frac{1}{m} \int_0^{t_0} p(t) dt,$$

and considering again a negligibly small displacement at the end of the loading,  $x(t_0) \approx 0$ , one has

$$x(t - t_0) \approx \frac{1}{m\omega_n} \int_0^{t_0} p(t) dt \sin \omega_n(t - t_0).$$

Please note that the above equation is exact for an infinitesimal impulse loading.

$$dx(t - \tau) = \frac{p(\tau) d\tau}{m\omega_n} \sin \omega_n(t - \tau), \quad t > \tau,$$

## Undamped SDOF

For an infinitesimal impulse, the impulse-momentum is exactly  $p(\tau) d\tau$  and the response is

$$dx(t - \tau) = \frac{p(\tau) d\tau}{m\omega_n} \sin \omega_n(t - \tau), \quad t > \tau,$$

and to evaluate the response at time  $t$  one has simply to sum all the infinitesimal contributions for  $\tau < t$ ,

$$x(t) = \frac{1}{m\omega_n} \int_0^t p(\tau) \sin \omega_n(t - \tau) d\tau, \quad t > 0.$$

This relation is known as the Duhamel integral, and tacitly depends on initial rest conditions for the system.

**Damped SDOF**

The derivation of the equation of motion for a generic load is analogous to what we have seen for undamped SDOF, the infinitesimal contribution to the response at time  $t$  of the load at time  $\tau$  is

$$dx(t) = \frac{p(\tau)}{m\omega_D} d\tau \sin \omega_D(t - \tau) \exp(-\zeta\omega_n(t - \tau)) \quad t \geq \tau$$

and integrating all infinitesimal contributions one has

$$x(t) = \frac{1}{m\omega_D} \int_0^t p(\tau) \sin \omega_D(t - \tau) \exp(-\zeta\omega_n(t - \tau)) d\tau, \quad t \geq 0.$$

**Evaluation of Duhamel integral, undamped**

Using the trig identity

$$\sin(\omega_n t - \omega_n \tau) = \sin \omega_n t \cos \omega_n \tau - \cos \omega_n t \sin \omega_n \tau$$

the Duhamel integral is rewritten as

$$\begin{aligned} x(t) &= \frac{\int_0^t p(\tau) \cos \omega_n \tau d\tau}{m\omega_n} \sin \omega_n t - \frac{\int_0^t p(\tau) \sin \omega_n \tau d\tau}{m\omega_n} \cos \omega_n t \\ &= \mathcal{A}(t) \sin \omega_n t - \mathcal{B}(t) \cos \omega_n t \end{aligned}$$

where

$$\begin{cases} \mathcal{A}(t) = \frac{1}{m\omega_n} \int_0^t p(\tau) \cos \omega_n \tau d\tau \\ \mathcal{B}(t) = \frac{1}{m\omega_n} \int_0^t p(\tau) \sin \omega_n \tau d\tau \end{cases}$$

**Numerical evaluation of Duhamel integral, undamped**

Usual numerical procedures can be applied to the evaluation of  $\mathcal{A}$  and  $\mathcal{B}$ , e.g., using the trapezoidal rule, one can have, with  $\mathcal{A}_n = \mathcal{A}(n\Delta\tau)$ ,  $y_n = p(n\Delta\tau) \cos(n\Delta\tau)$  and  $z_n = p(n\Delta\tau) \sin(n\Delta\tau)$  we can write

$$\begin{aligned} \mathcal{A}_{n+1} &= \mathcal{A}_n + \frac{\Delta\tau}{2m\omega_n} (y_n + y_{n+1}), \\ \mathcal{B}_{n+1} &= \mathcal{B}_n + \frac{\Delta\tau}{2m\omega_n} (z_n + z_{n+1}). \end{aligned}$$

## Evaluation of Duhamel integral, damped

For a damped system, it can be shown that

$$x(t) = A(t) \sin \omega_D t - B(t) \cos \omega_D t$$

with

$$A(t) = \frac{\exp -\zeta \omega_n t}{m \omega_D} \int_0^t p(\tau) \exp \zeta \omega_n \tau \cos \omega_D \tau d\tau,$$

$$B(t) = \frac{\exp -\zeta \omega_n t}{m \omega_D} \int_0^t p(\tau) \exp \zeta \omega_n \tau \sin \omega_D \tau d\tau.$$

## Numerical evaluation of Duhamel integral, damped

Numerically, using e.g. Simpson integration rule and  $y_n = p(n\Delta\tau) \cos \omega_D \tau$ ,

$$\mathcal{A}_{n+2} = \mathcal{A}_n \exp(-2\zeta \omega_n \Delta\tau) +$$

$$\frac{\Delta\tau}{3m\omega_D} [y_n \exp(-2\zeta \omega_n \Delta\tau) + 4y_{n+1} \exp(-\zeta \omega_n \Delta\tau) + y_{n+2}]$$

$$n = 0, 2, 4, \dots$$

(You can write a similar relationship for  $\mathcal{B}_{n+2}$ )

$H(\omega)$  vs  $h(t)$

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## Transfer Functions

The response of a linear SDOF system to arbitrary loading can be evaluated by a convolution integral in the time domain,

$$x(t) = \int_0^t p(\tau) h(t - \tau) d\tau,$$

with the unit impulse response function  $h(t) = \frac{1}{m\omega_D} \exp(-\zeta\omega_n t) \sin(\omega_D t)$ , or through the frequency domain using the Fourier integral

$$x(t) = \int_{-\infty}^{+\infty} H(\omega) P(\omega) \exp(i\omega t) d\omega,$$

where  $H(\omega)$  is the complex frequency response function.

## Transfer Functions

These response functions, or *transfer functions*, are connected by the direct and inverse Fourier transforms:

$$H(\omega) = \int_{-\infty}^{+\infty} h(t) \exp(-i\omega t) dt,$$

$$h(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} H(\omega) \exp(i\omega t) d\omega.$$

## Relationship of transfer functions

We write the response and its Fourier transform:

$$x(t) = \int_0^t p(\tau) h(t - \tau) d\tau = \int_{-\infty}^t p(\tau) h(t - \tau) d\tau$$

$$X(\omega) = \int_{-\infty}^{+\infty} x(t) \exp(-i\omega t) dt = \int_{-\infty}^{+\infty} \left[ \int_{-\infty}^t p(\tau) h(t - \tau) d\tau \right] \exp(-i\omega t) dt$$

where we changed the lower limit of integration, in the first equation, from 0 to  $-\infty$  because  $p(\tau) = 0$  for  $\tau < 0$ .

Since  $h(t - \tau) = 0$  for  $\tau > t$ , the upper limit of the second integral in the second equation can be changed from  $t$  to  $+\infty$ ,

$$X(\omega) = \lim_{s \rightarrow \infty} \int_{-s}^{+s} \int_{-s}^{+s} p(\tau) h(t - \tau) \exp(-i\omega t) dt d\tau$$

## Relationship of transfer functions

Introducing a new variable  $\theta = t - \tau$  we have

$$X(\omega) = \lim_{s \rightarrow \infty} \int_{-s}^{+s} p(\tau) \exp(-i\omega\tau) d\tau \int_{-s-\tau}^{+s-\tau} h(\theta) \exp(-i\omega\theta) d\theta$$

with  $\lim_{s \rightarrow \infty} s - \tau = \infty$ , we finally have

$$\begin{aligned} X(\omega) &= \int_{-\infty}^{+\infty} p(\tau) \exp(-i\omega\tau) d\tau \int_{-\infty}^{+\infty} h(\theta) \exp(-i\omega\theta) d\theta \\ &= P(\omega) \int_{-\infty}^{+\infty} h(\theta) \exp(-i\omega\theta) d\theta = P(\omega) H(\omega) \end{aligned}$$

where we have recognized that the first integral is the Fourier transform of  $p(t)$ .

## Relationship of transfer functions

Our last relation was

$$X(\omega) = P(\omega) \int_{-\infty}^{+\infty} h(\theta) \exp(-i\omega\theta) d\theta$$

but  $X(\omega) = H(\omega)P(\omega)$ , so that, noting that in the above equation the last integral is just the Fourier transform of  $h(\theta)$ , we may conclude that, effectively,  $H(\omega)$  and  $h(t)$  form a Fourier transform pair.