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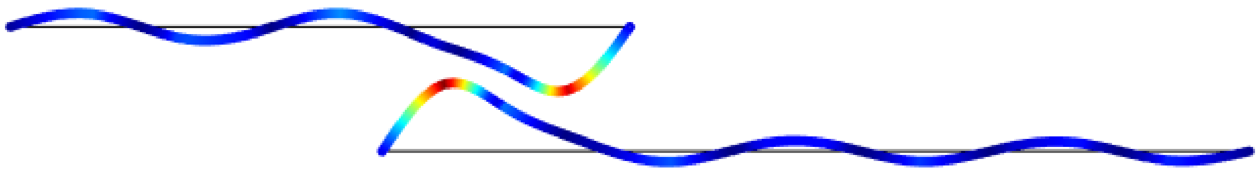

Time domain approach to identify system properties in coupled structures

Master of Science Thesis in Master's Programme Sound and Vibration

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Division of Applied Acoustics
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Master's thesis 2016:2

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Abstract

In this thesis, coupled structures which consist of two beams that are coupled with a spring between them has been studied. Free mobilities are identified as system properties of the coupled structure. The first approach was a virtual study comparing the free mobilities from the simulation and using the time domain approach. LMS algorithm is used to solve the equations in the time domain. Next step is to use the same method and apply in different degrees of freedom (one degree, two degrees) to calculate the error between the two methods. Lastly, the effect of some of the parameters like spring constant, isotropic loss factor, and damping coefficient are observed .The results in first two cases suggested that in one degree and two degrees the free mobilities of the sending and receiving points can be recreated almost accurately. And among other parameters, the spring constant and isotropic loss factor have the most effect on the results.

LMS-algorithm, Free Mobilities, Time-domain, Degree of Freedom.

Acknowledgements

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On a more personal side, I thank my parents and lovely wife for their encouragement and their help, for giving me the chance to go study in Göteborg.

NAGIB MEHFUZ, Gothenburg, June 2016

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Notations

Symbols

c Speed of sound [m/s]
f Frequency [Hz]
j Imaginary number $j = \sqrt{-1}$
ω Angular frequency $2\pi f$[Hz]
P Pressure [Pa]
L_p Sound pressure level $L_p = 20log_{10}|\frac{\tilde{p}}{p_{ref}}|$[dB]
N Number of samples
I Number of filter coefficients
μ Convergence Factor
ζ Mean Square error

Signals

$x(n)$ Input signal
$a(n)$ Desired signal
$e(n)$ Error signal
$y(n)$ Output signal

Abbreviatins

DOF Degree of Freedom
FFT Fast fourier transform
FIR Finite impulse function
FRF Frequency response function
IFRF Inverse frequency response function
LMS Least mean square

1
Introduction

1.1 Purpose and Background

Coupled structures are widely used in the modern era mostly in order to transmit power from one part to another of a structure. For example coupling in gear train allows the power to be transmitted from engine to wheel in order to drive the vehicle [5]. To ensure desired power transmission, identifying the system properties of the coupled structures are very important. But identifying the system properties of coupled structures is a bit complicated. Generally, to identify any system or force acting on a structure, free velocities and free mobilities of the structure are required. For coupling structure, free velocities and free mobilities at the connectors between the excitation and receiving structure should be calculated. It requires decoupling of both structures. In practice, decoupling sometimes becomes very complicated for complex structures. Properties of the connectors might change while decoupling. So measuring system properties without decoupling the structure are necessary.

There are few approaches that can calculate the system properties without decoupling the structure. Among them, the Principal Method (PM) is the most common[5]. It is an inverse approach where the response of the system is known and with the help of the model, the unknown excitation on the system can be calculated [14]. The free velocity and free mobility are calculated in the frequency domain.

Figure 1.1: The inverse Problem

Like most other inverse approaches, this method is also very sensitive to measurement imperfections. So, time domain approach is proposed by Kropp and Peviç [1] that is combined with the PM method. In this thesis a similar approach is followed to make the process more robust with respect to the 'measurement noise'.

In time domain approach the frequency response of the system is converted into the impulse response. And rather than solving the problem by inverse matrix method in the frequency domain, it solves the response in the time domain using an algorithm. Among different algorithms, Least Mean Square (LMS) algorithm is used in this method. It is widely used for adaptive filter design and system identification in the field of active noise control. While taking an inverse of the measured transfer function, the main advantage of LMS algorithm is that, the effect of noise during measurement is ignorable[2][3][4]. The algorithm is easy to implement and robust to measuremnt noise. The application of the LMS algorithm in the field of structure-borne sound for the identification of forces on structures were introduced by Kropp and Larsson[7].

1.2 Scope

The main aim of this thesis can be divided into 3 parts.

1.Investigation of the functioning of the Principle Method approach when combined with the Time domain approach.

2.Existing experimental work of two degree of freedom coupling system is extended by using simulation and also include couplings up to three degrees of freedom.

3.To identify the influence of some parameters like Spring constant, Isotropic loss factor and Damping coefficient in LMS prediction.

1.3 Limitations and Assumptions

This coupled structure is attached by an elastic joint. It is assumed that the mounts between the two structures are massless[6]. According to this assumption, coupling forces become identical on both sides of the coupling mounts. In previous work of Wolfgang and Peviç [1] it is shown that this assumption in many practical cases are acceptable. This method can potentially produce good results. The functioning of this method was shown for two beams, coupled by a mount.

1.4 Outline of the report

In this report, chapter 2 describes the theory of the LMS algorithm and different parameters. Chapter 3 explains methods, that are used in this thesis and how the PM method is combined with the time domain approach. The combined method is described with up to three degrees of freedom. In chapter 4 results and discussion about different cases for 1st and 2nd DoF of free mobility and error is presented. Conclusion and further work in this field are proposed in chapter 5 and 6 respectively.
.

2

Theory

2.1 Coupled Structure

Two separate structures can be coupled in different ways e.g. it can be a rigid coupling, an elastic coupling etc. Elastic coupling enables the force and moment of one structure to be transmitted into the other structure. And to understand the whole system the elastic mounting properties need to be identified.

2.2 Mobility

In simple words, mobility is a measure of how easy is it to vibrate the structure .The mobility can be defined as a function of the dynamic force acting at a point on the structure to its resulting velocity. It is the ratio of the response (i.e. Velocity) to the input (i.e. Force) [1] and is given by,

$Mobility = \frac{Velocity}{Force}$

The above description of mobility can be called as 'Frequency Response Function'(FRF') which provides information about the magnitude and the phase relationships between the output response and input excitation. The FRF' can also be expressed in terms of 'Accelerance' and 'Compliance' which can be expressed as shown below,

$Accelerance = \frac{Acceleration}{Force}$

$Compliance = \frac{Displacement}{Force}$

When plotted against frequency all these Frequency Response Functions provide the same information. However, a practical reason for choosing mobility over other types of FRF is that the average mobility spectrum is a constant line which optimizes the range of y-axis when plotting the FRF. The compliance and accelerance results in a falling/rising pattern of the average spectrum when plotted against frequency which would otherwise require a wider range of values on the y-axis. Another reason of choosing mobility is that it is based on the velocity and is directly related to the kinetic energy of the structure. So to analyze system properties free mobility can be an important tool.

2.2.1 Driving Point Mobility

A driving point mobility or input mobility is an FRF between an input and an output signal at the same point. For dynamic testing, this is most commonly the FRF obtained when the exciter and the accelerometer are positioned at the same DOF (node and direction).

2.2.2 Transfer Mobility

The transfer mobility is one where an excitation such as a shaker or a hammer is used to excite the structure and the resulting vibration is measured at various locations on the test structure using an accelerometer or any transducer which can measure vibrations.

2.3 The Least Mean Square (LMS) Algorithm

The LMS algorithm is frequently used for designing adaptive filters and in the field of active noise control. In this case, LMS algorithm is used to identify the unknown force in coupling structure in time domain. Figure 2.1 shows a typical design condition where a_d is output of an unknown system h_0. By using a Finite Impulse Response (FIR) filter h, having a length of I the output can be reconstructed. The error e of both outputs can be calculated by the expression below

$$e(n) = a_d(n) - \sum_{i=0}^{I-1}(x(n-i)h(i)) \tag{2.1}$$

Where x is the observed input into the system. The filter and the input is written in vector form as.

$$e(n) = a_d(n) - h^T x(n) \tag{2.2}$$

Here the transpose of the filter h is taken.

h=[h(0),h(1),. . . . . . $h(I-1)]^T$

and

x=[x(n),h(n-1),. . . . . . $h(n-I+1)]^T$

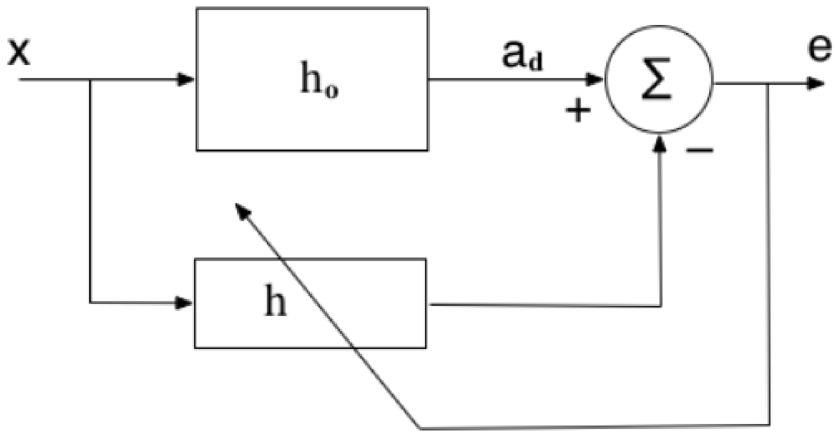

Figure 2.1: Block Diagram of the filter design according to LMS algorithm

To minimize the mean value of the quadratic error the LMS algorithm is used.

$$Mean[e^2] = Mean[(a_d - h^T x(n))^2] \tag{2.3}$$

By taking the derivative with respect to the filter coefficients h_i the optimal filter can be found. It is known as Wiener filter.

$$\frac{\partial Mean[e^2]}{\partial h_i} = 2Mean[e(n)\frac{\partial e(n)}{\partial h_i} = -2Mean[e(n)x(n-1)] \tag{2.4}$$

In equation2.3 is a quadratic with respect to the filter coefficients and to the values of the input signal. In the beginning, one can follow the steepest gradient but this process will end up to a point of a global minimum of error. From this an iterative method can be formulated for calculating the filter coefficients by expressing a set of new (updated) coefficients h_i (new) as

$$h_i(new) = h_i(old) - \alpha\frac{\partial Mean[e_2(n)}{\partial h_i} = h_i(old + 2\alpha Mean[e(n) - x(n-1)]) \tag{2.5}$$

Where α is a weighting factor, determining the step size in the iteration process. The gradient is expressed as ensemble average which is not easy to calculate. So the method of Widrow and Hoff [11] is used to solve this problem. It estimates the gradient from the instantaneous value of the gradient for each time step n. Using instantaneous gradient for each time will in average adjust the coefficients h_i in a way that reduces the mean square error. The expression is written in vector form below

$$H(n+1) = h(n) + \alpha e(nx(n)) \tag{2.6}$$

This formulation of the LMS algorithm will create a filter, which converges towards the Wiener filter solution. For the convergence coefficient, one finds as a ‘rule of thumb’ that it has to fulfill the following condition in order to achieve convergence.

$$0 < \alpha < \frac{1}{(IMean[x^2(n)]} \quad (2.7)$$

Due to the presence of noise, there might be some error in each time gradient but because of the iteration process, the averaged gradient will still head towards the global minimum. That makes the LMS algorithm robust in the presence of noise. A relative mean error is defined as

$$error = \frac{\sum_{n=I}^{N}[e(n)]^2}{\sum_{n=I}^{N}[a_d(n)]^2}.100 \quad (2.8)$$

2.4 Matlab implementation of LMS algorithm

2.4.1 Initialization

Initially, an arbitrarily long input signal s(n) is assumed. The aim is to estimate only N values of this input force. So a part of this arbitrary force signal will be the target source signal $s_0(n)$ of length N. Our force estimation vector is $\hat{s}(n)$ at time step n=0 as zero-vector of the same size as the target vector.

2.4.2 Adaptive process

In accordance with table 2.6 and above-mentioned assumption of periodicity, we apply an iterative process to adjust only I value of the force estimation vector at each time step. The procedure is broken down into 5 basic steps which will be repeated as steady sequence. The sequence is illustrated in table 2.1. Dimensions of vectors are specified by superscripts. These steps are mentioned below:

1. Pick out I values of the current force estimation vector $\hat{s}(n)$. "Current" means the previous update of the vector. To point out that for the considered time step n the selected I values are not updated yet and it is denoted by $\hat{s_{old}}(n)$.

2. The convolution of instantaneous force estimate $\hat{s_{old}}(n)$ and the impulse response function h_0 of the length I gives an estimated value for the recent filter output $\hat{x}n$.

3. The difference $e(n)$ is obtained by comparing the filter output $\hat{x}(n)$ with the desired signal $\hat{x_0}(n)$.

4. This error is then used to adjust the selected I values of the input force by weighting the filter and the step size parameter α . In this manner an adjusted version $\hat{s_{new}}(n)$ of the input sample is obtained

5. These adjusted vector is then used to update the selected I values of the instantaneous force estimation vector $\hat{s}(n)$.

Table 2.1: LMS algorithm for force estimation

Initialization	$\hat{s_{old}}(n)$=0
error	$e(n)$= $x_0(n)$-$\hat{x}n$ with $\hat{x}(n)$=$h_0^T\hat{s_{old}}(n)$
update	$\hat{s_{new}}(n)$= $\hat{s_{old}}(n)$+$\alpha e(n)h_0$ for $I \leq n \leq N$
parameters	α Step Size parameter I filter length N length of unknown force and system response

Table 2.2: Elementary Matlab Model

time step	explanation	equation
Initialization	Define zero-vector for force estimation of length N	$\hat{s}^{[N\times1]}$
adaptive process n=1	1. pick out a part of the input signal of length I	$\hat{s_{old}}^{[I\times1]}$=$\hat{s}(n:-1:n-I+1)$
	2. convolution h_0 and $\hat{s_{old}}$ to get an estimation $\hat{x}(n)$ of the output	$\hat{x}(n)$=$h_0^T\hat{s_{old}}(n)$
	3. compare estimate $\hat{x}(n)$ with measured output $\hat{x_0}(n)$ to get the error	$e(n)$= $x_0(n)$-$\hat{x}n$
	4. adjust the input sample by use if the error	$\hat{s_{old}}^{[I*1]}$= $\hat{s_{old}}(n)$+$\alpha e(n)h_0$
	5. update the adjusted I sample in the estimation vector	$\hat{s}^{[I\times1]}$(n:-1:n-I+1)=$\hat{s_{new}}$

Table 2.3: Different Dependency

Type of Model	Real part of the modulus D	imaginary part of the modulus D	loss factor
Loss Factor	D	η_0D	η_0

2.5 Degree of freedom

The term degree of freedom (DoF) is widely used in structural dynamics. It determines the orientation of a body or system. In simple words, it is the number of independent coordinates. For example, a one-dimensional system a point will have one degree of freedom.

2.6 Spring Constant

When an object applies a force to a spring, then the spring applies an equal and opposite force to the object. According to the hook's law, it can be written that

F = –kx
where K is called the spring stiffness which reflects the strength of the spring. Minus sign shows that this force is in the opposite direction of the force that is stretching or compressing the spring. The distance from the equilibrium position of the spring is denoted by X

The force exerted by a spring is called a restoring force becasue it always acts to restore the spring toward equilibrium.

2.7 Isotropic Loss factor

Material damping mechanism transforms the vibration energy of the material into another form of energy like heat There are different types of model that can be used to describe the material damping. Among them, is the loss factor model is one of them. the main difference between different types of model is their dependency on the frequency of the material. The real part and the imaginary part of the modulus (stiffness) shown in table 2.3

2.8 Damping Coefficient

Damping coefficient is the parameter of the elastic mounting. Mass and stiffness proportional damping, normally referred to as Rayleigh damping, is commonly used in a nonlinear-dynamic analysis. Suitability for an incremental approach to numerical solution merits its use. During formulation, the damping matrix is assumed to be proportional to the mass and stiffness matrices as follows:

$$c = \delta K + \eta M \tag{2.9}$$

where:
η is the mass-proportional damping coefficient; and
δ is the stiffness proportional to damping coefficient.

3
Methods

3.1 The Principle Method for 1st Degree of Freedom

Principle method is implemented in the frequency domain. A combined approach that was introduced by Wolfgang Kropp and Goran Paviç is followed[1], where the results from the frequency domain were used in the time domain to estimate the free mobilities.

3.1.1 Frequency Domain

Figure 3.1 the coupled structure is characterized by their free mobilities Y_s, Y_r. Y_s stands for the mobility of the source structure (in some cases represented as sending structure). Y_r for that of the receiver structure. In frequency domain, the equations for the forces along with the coupling force are formatted.

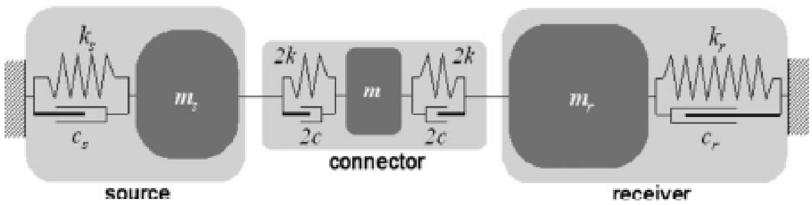

Figure 3.1: Sending and receiving structure coupled with an elastic mount[1]

3.1.1.1 Equation Formation

The mounted properties are needed to identify the unknown mobilities. For the ideal case, the mounting properties are known. But for this method, it was assumed that the mass of the mount is zero. It shows better results than badly guessed mounted properties which were proved by Paviç, G., and Elliott, A.[6].

To find the unknown free mobilities two set of measurements are needed. In the first set, the sending system is excited at the coupling point and the response at sending and receiving side are measured. The equation for the excitation of the sending structure is given below. 's' and 'r' indicate the sending and receiving structures.

The first index determines the side from which the response is taken and the second index indicates the excitation side [1].

In the first case, the sending structure was excited which leads to

$$F_{s0}Y_s + F_{c,s}Y_s = v_{s,s} \tag{3.1}$$

$$F_{c,s}Y_r = v_{r,s} \tag{3.2}$$

$$F_{c,s} = -Z(v_{s,s} + v_{r,s}) \tag{3.3}$$

where,
F_{s0}= Force excitation on sending beam
$F_{c,s}$= Coupling force of the mount when the excitation was in the sending beam
$v_{s,s}$=velocity of sending side when the excitation was in the sending beam
$v_{r,s}$=velocity of receiving side when the excitation was in the sending beam
Y_s=Free mobility of sending structure.
Y_r= Free mobility of receiving structure.
Z= Impedance of the mass-less mounts.

In the second case, the receiving structure was excited which leads to

$$F_{r0}Y_r + F_{c,r}Y_r = v_{r,r} \tag{3.4}$$

$$F_{c,r}Y_s = v_{s,r} \tag{3.5}$$

$$F_{c,r} = -Z(v_{s,r} + v_{r,r}) \tag{3.6}$$

where,
F_{r0}= Force excitation on receiving beam
$F_{r,s}$= Coupling force of the mount when the excitation was in the receiving beam
$v_{s,r}$=velocity of sending side when the excitation was in the receiving beam
$v_{r,r}$=velocity of receiving side when the excitation was in the receiving beam

From the equations 3.5 and 3.6 the new variable ZY_s can be determined which was the product of the sending free mobility and unknown impedance of the massless mount. From 3.1 and 3.3 the free mobility of the sending structure Y_s for 1st DoF excitation and response can be determined. Later on, it is explained in detail.

$$-Z(v_{s,r} + v_{r,r})Y_s = v_{s,r} \tag{3.7}$$

$$F_{s0}Y_s - Z(v_{s,s} + v_{r,s}) = v_{s,s} \tag{3.8}$$

Similarly, from the equations 3.2 and 3.3 the new variable ZY_r can be determined. To identify the free mobility of the receiving structure Y_r, equations 3.4 and 3.5 are used.

$$-Z(v_{s,s} + v_{r,s})Y_r = v_{r,s} \tag{3.9}$$

$$F_{r0}Y_r - Z(v_{s,r} + v_{r,r})Y_r = v_{r,r} \tag{3.10}$$

There are few things that should be kept in mind for solving those equations. To find out the velocity the frequency domain is the best approach. Initially, that was found by the Comsol simulation. Then those equations can be solved in the time domain where the LMS algorithm was used.

3.1.2 Time Domain Formulation

In the time domain, two strategies could be followed to formulate the set of equations in a way which was suitable for applying the LMS algorithm. The first approach focuses on treating the equation system as a network of filters. A second approach would be using a symbolic toolbox to solve the equations at first and then implement just one single filter for each unknown mobilities. The first approach was followed here.

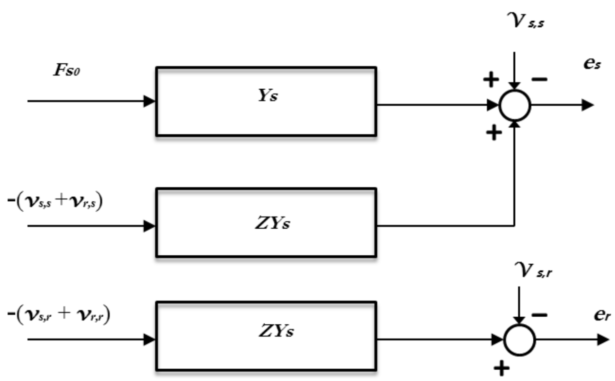

Figure 3.2: Formation of equation as network of filters suitable for the LMS algorithm

Frequency response functions for the coupled system are determined first. By using inverse Fourier transforms the impulse response functions are calculated. To identify the measured velocity, the impulse response function can then be convoluted with the time records of the excitation force. Using the equations 2.6 and 2.7 the LMS algorithm is implemented, where it is used to determine the unknown impulse response function ZY_s. Depending on the results the impulse response function of the free mobilities is calculated. The iterative process aborted either by reaching a prescribed minimum error or by exceeding a prescribed maximum number of iterations.

3.2 Two Degree of Freedom System

For two degrees of freedom elastic mount, two beams are considered coupled, i.e. displacement and bending angle. It is considered that there are two degrees of freedom in excitation and two degrees of freedom in response. For this thesis, 1st DoF excitation is a force in the y-direction (perpendicular to the beam) and 2nd DoF excitation is the moment. Similarly, the 1st DoF of response is the velocity in the y-direction and 2nd DoF is taken angular velocity in Z direction in comsol.

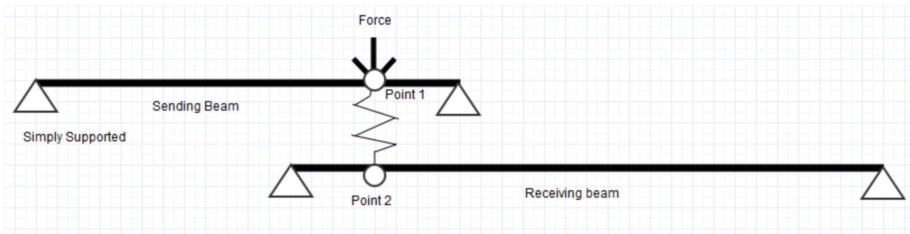

Figure 3.3: Two beam and spring when force is applied in point 1

In the figure3.3, there are two points mentioned in two beams: one in the sending beam denoted as point 1 and another in the receiving beam denoted as point 2. In this thesis, sending beam only represent point 1 and receiving beam only represents point 2.

To understand the two-dimensional phenomenon, it is divided into four cases. In table3.1 a clear picture can be found that for each case there are two possibilities. In 1st DOF, One option is the unknown force applied to point 1 and the response are taken both in point 1 and point 2 as velocity or the force is applied to point 2 and the response is taken in point 1 and point 2 as velocity. In 2nd DOF, instead of unknown force, an unknown moment is applied and for response, angular velocity is taken.
For each case, there are four velocities. In total for four cases, there are 16 velocities. The new variables were defined as v_{snm} and v_{rnm} where, n=1,2 and m=1,..,4.For the velocities describing the coupled structures, the first index concerns the receiving point the second index indicates the excitation case.

n=1: refers to sending beam n=2: refers to receiving Beam

m=1: excitation on the sending structure (point 1) in DoF 1-force

Table 3.1: Different Case Conditions

c

Cases	Excitation		Response	
	Position	**DoF**	**Position**	**DoF**
Case 1	Point 1	1st	Point 1 and Point 2	1st
	Point 2	1st	Point 1 and Point 2	1st
Case 2	Point 1	2nd	Point 1 and Point 2	1st
	Point 2	2nd	Point 1 and Point 2	1st
Case 3	Point 1	1st	Point 1 and Point 2	2nd
	Point 2	1st	Point 1 and Point 2	2nd
Case 4	Point 1	2nd	Point 1 and Point 2	2nd
	Point 2	2nd	Point 1 and Point 2	2nd

m=2: excitation on the sending structure (point 1) in DoF 2-moment

m=3: excitation on the receiving structure (point 2) in DoF 1-force

m=4: excitation on the receiving structure (point 2) in DoF 2-moment

Again, for each case two free mobilities can be calculated. One for the sending beam in point 1 and another is the receiving beam in point 2. In total, for four cases 8 free mobilities are found. Y_{sab}, Y_{rab} where, 's' denoted the sending beam,'r' denoted receiving beam. Then, the first index 'a' determines the DoF of the excitation, the second index 'b' indicates the DoF of the response.

a=1: 1st degree of excitation
a=2: 2nd degree of excitation
b=1: 1st degree of response
b=2: 2nd degree of response

Y_{s11}, Y_{s12}, Y_{s21}, Y_{s22} and Y_{r11}, Y_{r12}, Y_{r21}, Y_{r22} are the four sending free mobilities and four receiving free mobilities are needed for describing the whole structure.. There are also eight unknowns (ZY_{s11}, ZY_{s12}, ZY_{s21}, ZY_{s22} and ZY_{r11}, ZY_{r12}, ZY_{r21}, ZY_{r22}) due to the unknown coupling forces.

In total, there are sixteen unknowns to deal with, but the equation system can be easily divided into successive steps where first the terms related to the coupling forces are calculated and then the free mobilities as it was shown in the previous section.

For each case force is motioned either F_{sp} or F_{rp} where 's' denoted the sending beam,'r' denoted receiving beam, p=1 means the 1st degree of freedom or p=2 for the 2nd degree of freedom. Coupling forces are denoted by $F_{c,sq}$ and $F_{c,rq}$. where 's' denoted the sending beam,'r' denoted receiving beam, q=1 means 1st degree of freedom or q=2 for 2nd degree of freedom.

The equations for the four cases are mentioned below and solved by a network of filter processes to get the free mobilities that are desired.

3.2.1 Case 1

In case 1, as stated in table 3.1 for each excitation response is taken into two points. 1st DoF excitation in point 1 leads to 3 equations below.

$$F_{s1}Y_{s11} + F_{c,s1}Y_{s11} = v_{s11} \tag{3.11}$$

$$F_{c,s1}Y_{r11} = v_{r11} \tag{3.12}$$

$$F_{c,s1} = -Z(v_{s11} + v_{r11}) \tag{3.13}$$

For the excitation in the receiving structure at point 2, the equations can be constructed as follows

$$F_{r1}Y_{r11} + F_{c,r1}Y_{r11} = v_{r13} \tag{3.14}$$

$$F_{c,r1}Y_{s11} = v_{s13} \tag{3.15}$$

$$F_{c,r1} = -Z(v_{r13} + v_{s13}) \tag{3.16}$$

From the equations 3.15, 3.16, 3.11 and 3.12 two equations can be determined.

$$-ZY_{s11}(v_{s13} + v_{r13}) = v_{s13} \tag{3.17}$$

$$F_{s1}Y_{s11} - ZY_{s11}(v_{s11} + v_{r11}) = v_{s11} \tag{3.18}$$

By solving these two equations 3.17 and 3.18 by filter network system the free mobility of the sending structure Y_{s11} for 1st DoF of excitation and response can be determined.First the equation 3.17 is represented by the filter below. Where $(v_{s13} + v_{r13})$ is the input of the filter. v_{s13} is the desired output from the filter. As the input and output are known, the unknown filter coefficient ZY_{s11} can be determined by using LMS algorithm where the optimal goal is to minimize the error e_r.

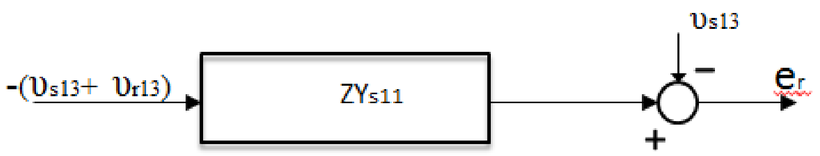

Figure 3.4: Formation of equation as network of filter suitable for the LMS algorithm for ZY_{s11}

Using the information ZY_{s11}, the free mobility Y_{s11} is calculated by forming another filter network mentioned below. The desired output is $v_{s11} + ZY_{s11}(v_{s11} + v_{r11})$ and the input F_{s1} is taken as one. So the unknown filter coefficient, whcih represnt the free mobility Y_{s11} can be determined by LMS algorithm.

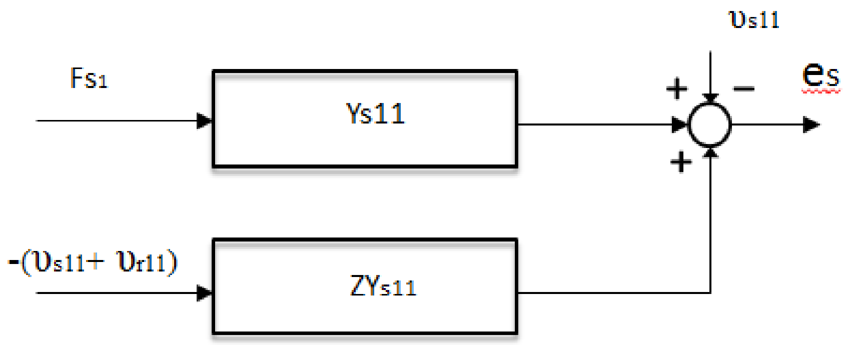

Figure 3.5: Formation of equation as network of filter suitable for the LMS algorithm for Y_{s11}

Similarly,Y_{r11} can be determined by solving the equations 3.11, 3.12, 3.13 and 3.14. Other cases also follow the same procedure. So equations those are needed to identify the free mobility in sending beam point 1 are mentioned only for the rest of the cases. Then they are represented in a filter network diagram.Free mobility of the receiving beam at point 2 can also be calculated in a similar way.

3.2.2 Case 2

For the excitation in the sending structure, the equations can be constructed as follows

$$F_{s2}Y_{s21} + F_{c,s2}Y_{s21} = v_{s12} \tag{3.19}$$

$$F_{c,s2}Y_{r21} = v_{r12} \tag{3.20}$$

$$F_{c,s2} = -Z(v_{s12} + v_{r12}) \tag{3.21}$$

For the excitation in the receiving structure, the equations can be constructed as follows

$$F_{r2}Y_{r21} + F_{c,r2}Y_{r21} = v_{r14} \tag{3.22}$$

$$F_{c,r2}Y_{s21} = v_{s14} \tag{3.23}$$

$$F_{c,r1} = -Z(v_{r14} + v_{s14}) \tag{3.24}$$

From the equations 3.23, 3.24, 3.19 and 3.20 the free mobility of the sending structure Y_{s21} for 2nd DoF of excitation and 1st DoF of response can be determined following the filter network mentioned above.

$$-Z(v_{s14} + v_{r14})Y_{s21} = v_{s14} \tag{3.25}$$

$$F_{s2}Y_{s21} - Z(v_{s12} + v_{r12})Y_{s21} = v_{s12} \tag{3.26}$$

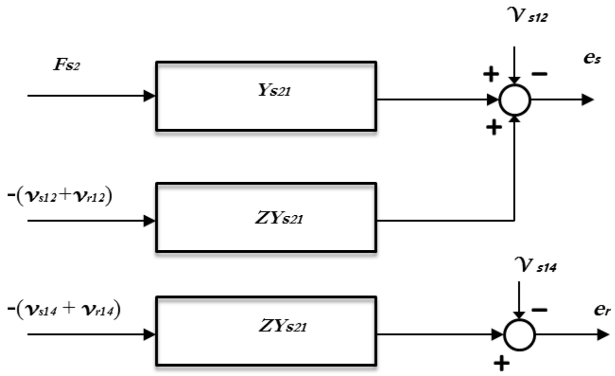

Figure 3.6: Formation of equation as network of filters suitable for the LMS algorithm for Y_{s21}

3.2.3 Case 3

: For the excitation in the sending structure, the equations can be constructed as follows

$$F_{s1}Y_{s12} + F_{c,s1}Y_{s12} = v_{s21} \tag{3.27}$$

$$F_{c,s1}Y_{r12} = v_{r21} \tag{3.28}$$

$$F_{c,s1} = -Z(v_{s21} + v_{r21}) \tag{3.29}$$

For the excitation in the receiving structure, the equations can be constructed as follows

$$F_{r1}Y_{r12} + F_{c,r1}Y_{r12} = v_{r23} \tag{3.30}$$

$$F_{c,r1}Y_{s12} = v_{s23} \tag{3.31}$$

$$F_{c,r1} = -Z(v_{r23} + v_{s23}) \tag{3.32}$$

From the equation 3.31, 3.32, 3.27 and 3.29 the free mobility of the sending structure Y_{s12} for 1st DoF excitation and 2nd DoF response can be determined following the filter network mentioned above.

$$-Z(v_{s23} + v_{r23})Y_{s12} = v_{s23} \tag{3.33}$$

$$F_{s1}Y_{s12} - Z(v_{s21} + v_{r21})Y_{s12} = v_{s21} \tag{3.34}$$

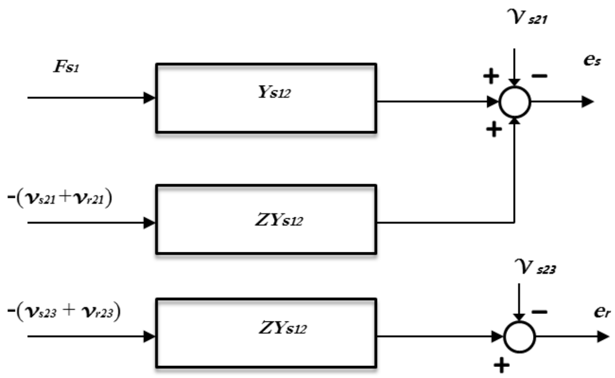

Figure 3.7: Formation of equation as network of filters suitable for the LMS algorithm for Y_{s12}

3.2.4 Case 4

For the excitation in the sending structure, the equations can be constructed as follows

$$F_{s2}Y_{s22} + F_{c,s2}Y_{s22} = v_{s22} \tag{3.35}$$

$$F_{c,s2}Y_{r22} = v_{r22} \tag{3.36}$$

$$F_{c,s2} = -Z(v_{s22} + v_{r22}) \tag{3.37}$$

For the excitation in the receiving structure, the equations can be constructed as follows

$$F_{r2}Y_{r22} + F_{c,r2}Y_{r22} = v_{r24} \tag{3.38}$$

$$F_{c,r2}Y_{s22} = v_{s24} \tag{3.39}$$

$$F_{c,r2} = -Z(v_{r24} + v_{s24}) \tag{3.40}$$

From the equations 3.39, 3.40, 3.35 and 3.37 the free mobility of the sending structure Y_{s22} for 2nd DoF of excitation and 2nd DoF of response can be determined following the filter network mentioned above.

$$-Z(v_{s24}+v_{r24})Y_{s22}=v_{s24} \tag{3.41}$$

$$F_{s2}Y_{s22}-Z(v_{s22}+v_{r22})Y_{s22}=v_{s22} \tag{3.42}$$

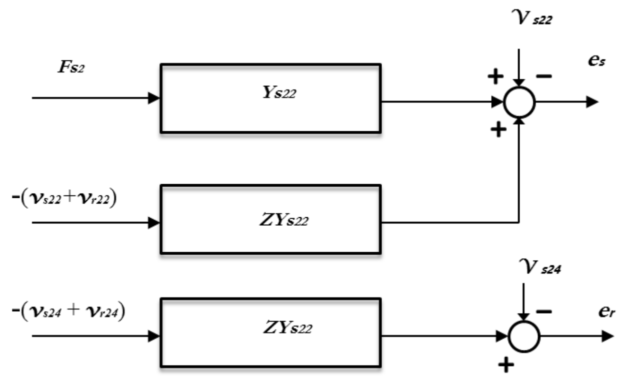

Figure 3.8: Formation of equation as network of filters suitable for the LMS algorithm for Y_{s22}

3.3 Three Degree of Freedom System

For this thesis, three degree of freedom excitation and response is considered. The excitation is the force in the x-direction while the response is the velocity in x-direction. So there are some additional cases needed to be consider, where 3rd DoF of excitation and 3rd DoF of response are applied. Calculation of 5 more steps are needed to analyze the coupling system mentioned above.
For the velocities describing the coupled structures, indexing is almost same as mentioned in 2nd DoF system. Only in second index two more variable are added due to 3rd DoF system

m=5: excitation on the sending structure in DoF 3- force in x direction

m=6: excitation on the receiving structure in DoF 3- force in x direction

Table 3.2: Different Case Conditions

c

Cases	Excitation		Response	
	Position	**DoF**	**Position**	**DoF**
Case 5	Point 1	1st	Point 1 and Point 2	3rd
	Point 2	1st	Point 1 and Point 2	3rd
Case 6	Point 1	3rd	Point 1 and Point 2	1st
	Point 2	3rd	Point 1 and Point 2	1st
Case 7	Point 1	3rd	Point 1 and Point 2	2nd
	Point 2	3rd	Point 1 and Point 2	2nd
Case 8	Point 1	2nd	Point 1 and Point 2	3rd
	Point 2	2nd	Point 1 and Point 2	3rd
Case 9	Point 1	3rd	Point 1 and Point 2	3rd
	Point 2	3rd	Point 1 and Point 2	3rd

To analyze the whole system calculations regarding ten extra monilities for five cases is to be performed. The indexing pattern is almost similar as 2 DoF coupling system. Y_{sab} and Y_{rab}, where only the values of 'a','b' can be up to three. a=3: 3rd degree of excitation
b=3: 3rd degree of respnse

Five mobilities in sending beam: Y_{s13}, Y_{s31}, Y_{s32}, Y_{s23}, Y_{s33} and other five in receiving beam: Y_{r13}, Y_{r31}, Y_{r32}, Y_{r23}, Y_{r33}. There are also like the 2 DoF system,ten unknowns ZY_{s13}, ZY_{s31}, ZY_{s32}, ZY_{s23}, ZY_{s33} and ZY_{r13}, ZY_{r31}, ZY_{r32}, ZY_{r23}, ZY_{r33} due to the unknown coupling forces.

In total, there are twenty unknowns to deal with, luckily the equation system can be easily divided into successive steps where first the terms related to the coupling forces are calculated and then the free mobilities as it was shown in the previous section.

For each case force is motioned either F_{sp} or F_{rp} only new indexing is p=3 that means the 3rd degree of freedom excitation which is the force in the x direction. Coupling forces are denoted by $F_{c,sq}$ and $F_{c,rq}$. q=3 means the 3rd degree of freedom.
The equations for the five cases are mentioned below and solved by a network of filter process to get the free mobilities. This method only proposed for the 1st time in the in this thesis but not implemented in the simulation. Further work of this thesis will be the implementation of this method.

3.3.1 Case 5

The equations for the excitation in the sending structure can be constructed as follows

$$F_{s1}Y_{s13} + F_{c,s1}Y_{s13} = v_{s31} \tag{3.43}$$

$$F_{c,s1}Y_{r13} = v_{r31} \tag{3.44}$$

$$F_{c,s1} = -Z(v_{s31} + v_{r31}) \tag{3.45}$$

For the excitation in the receiving structure, the equations can be constructed as follows

$$F_{r1}Y_{r13} + F_{c,r1}Y_{r13} = v_{r33} \tag{3.46}$$

$$F_{c,r1}Y_{s13} = v_{s33} \tag{3.47}$$

$$F_{c,r1} = -Z(v_{r33} + v_{s33}) \tag{3.48}$$

From the equations 3.47, 3.48, 3.43 and 3.45 the free mobility of the sending structure Y_{s13} for 1st DoF of excitation and 3rd DoF of response can be determined following the filter network mentioned above.

$$-Z(v_{s33} + v_{r33})Y_{s13} = v_{s33} \tag{3.49}$$

$$F_{s1}Y_{s13} - Z(v_{s31} + v_{r31})Y_{s13} = v_{s31} \tag{3.50}$$

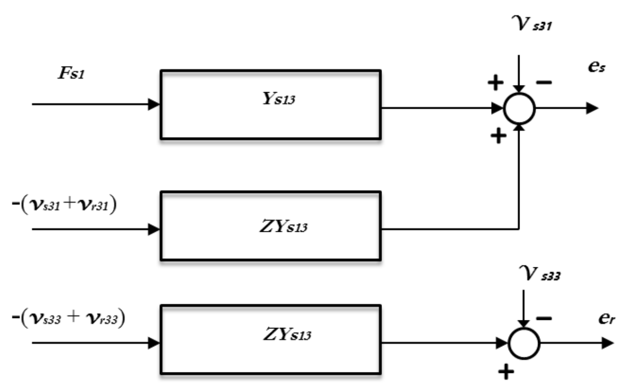

Figure 3.9: Formation of equation as network of filters suitable for the LMS algorithm for Y_{s13}

From the equations 3.44, 3.45, 3.46 and 3.47 the free mobility of the receiving structure Y_{r13} for 1st DoF of excitation and 3rd DoF of response can be determined following the filter network mentioned above.

$$- Z(v_{s31} + v_{r31})Y_{r13} = v_{r31} \tag{3.51}$$

$$F_{r1}Y_{r13} - Z(v_{s33} + v_{r33})Y_{r13} = v_{r33} \tag{3.52}$$

From this cases, it is found that methods to identify the free mobilities on point 1 of the sending beam and point 2 of the receiving beam are very similar. So to avoid the repetition, the method to get the free mobilities in point 1 is mentioned for the next four cases.

3.3.2 Case 6

For the excitation in the sending structure, the equations can be constructed as follows

$$F_{s3}Y_{s31} + F_{c,s3}Y_{s31} = v_{s15} \tag{3.53}$$

$$F_{c,s3}Y_{r31} = v_{r15} \tag{3.54}$$

$$F_{c,s3} = -Z(v_{s15} + v_{r15}) \tag{3.55}$$

For the excitation in the receiving structure, the equations can be constructed as follows

$$F_{r3}Y_{r31} + F_{c,r3}Y_{r31} = v_{r16} \tag{3.56}$$

$$F_{c,r3}Y_{s31} = v_{s16} \tag{3.57}$$

$$F_{c,r3} = -Z(v_{r16} + v_{s16}) \tag{3.58}$$

From the equations 3.57, 3.58, 3.53 and 3.55 the free mobility of the sending structure Y_{s31} for 1st DoF of excitation and 3rd DoF of response can be determined following the filter network mentioned above.

$$- Z(v_{s16} + v_{r16})Y_{s31} = v_{s16} \tag{3.59}$$

$$F_{s3}Y_{s31} - Z(v_{s15} + v_{r15})Y_{s31} = v_{s15} \tag{3.60}$$

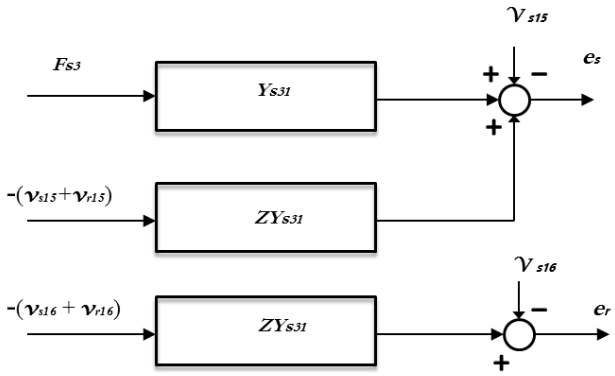

Figure 3.10: Formation of equation as network of filters suitable for the LMS algorithm for Y_{s31}

3.3.3 Case 7

For the excitation in the sending structure, the equations can be constructed as follows

$$F_{s3}Y_{s32} + F_{c,s3}Y_{s32} = v_{s25} \tag{3.61}$$

$$F_{c,s3}Y_{r32} = v_{r25} \tag{3.62}$$

$$F_{c,s3} = -Z(v_{s25} + v_{r25}) \tag{3.63}$$

$$F_{r3}Y_{r32} + F_{c,r3}Y_{r32} = v_{r26} \tag{3.64}$$

$$F_{c,r3}Y_{s32} = v_{s26} \tag{3.65}$$

$$F_{c,r3} = -Z(v_{r26} + v_{s26}) \tag{3.66}$$

From the equations 3.65, 3.66, 3.61 and 3.63 the free mobility of the sending structure Y_{s32} for 3rd DoF of excitation and 2nd DoF of response can be determined following the filter network mentioned above.

$$-Z(v_{s26} + v_{r26})Y_{s32} = v_{s26} \tag{3.67}$$

$$F_{s3}Y_{s32} - Z(v_{s25} + v_{r25})Y_{s32} = v_{s25} \tag{3.68}$$

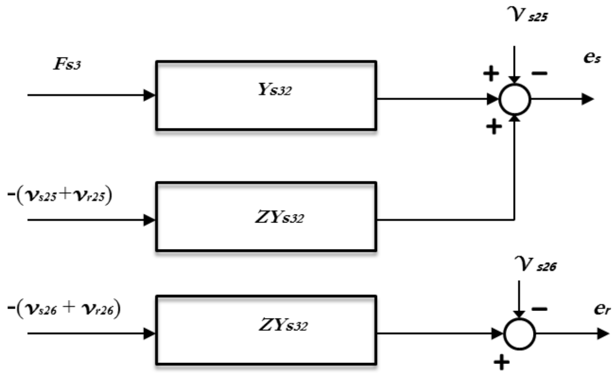

Figure 3.11: Formation of equation as network of filters suitable for the LMS algorithm for Y_{s32}

3.3.4 Case 8

For the excitation in the sending structure, the equations can be constructed as follows

$$F_{s2}Y_{s23} + F_{c,s2}Y_{s23} = v_{s32} \tag{3.69}$$

$$F_{c,s2}Y_{r23} = v_{r32} \tag{3.70}$$

$$F_{c,s2} = -Z(v_{s32} + v_{r32}) \tag{3.71}$$

For the excitation in the receiving structure, the equations can be constructed as follows

$$F_{r2}Y_{r23} + F_{c,r2}Y_{r23} = v_{r34} \tag{3.72}$$

$$F_{c,r2}Y_{s23} = v_{s34} \tag{3.73}$$

$$F_{c,r2} = -Z(v_{r34} + v_{s34}) \tag{3.74}$$

From the equations 3.73, 3.74, 3.69 and 3.71 the free mobility of the sending structure Y_{s34} for 2nd DoF of excitation and 3rd DoF of response can be determined following the filter network mentioned above.

$$-Z(v_{s23} + v_{r34})Y_{s34} = v_{s34} \tag{3.75}$$

$$F_{s2}Y_{s23} - Z(v_{s23} + v_{r32})Y_{s23} = v_{s32} \tag{3.76}$$

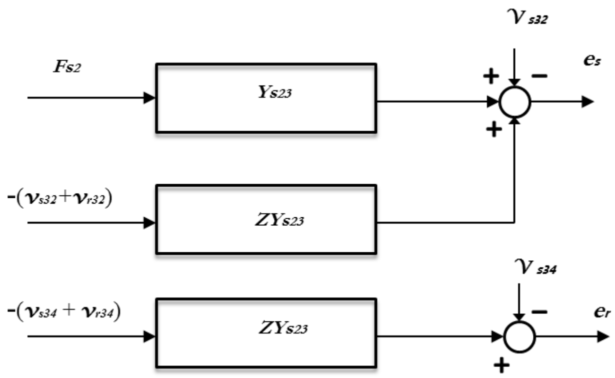

Figure 3.12: Formation of equation as network of filters suitable for the LMS algorithm for Y_{s34}

3.3.5 Case 9

For the excitation in the sending structure, the equations can be constructed as follows

$$F_{s3}Y_{s33} + F_{c,s3}Y_{s33} = v_{s35} \tag{3.77}$$

$$F_{c,s3}Y_{r33} = v_{r35} \tag{3.78}$$

$$F_{c,s3} = -Z(v_{s35} + v_{r35}) \tag{3.79}$$

For the excitation in the receiving structure, the equations can be constructed as follows

$$F_{r3}Y_{r33} + F_{c,r3}Y_{r33} = v_{r36} \tag{3.80}$$

$$F_{c,r3}Y_{s33} = v_{s36} \tag{3.81}$$

$$F_{c,r3} = -Z(v_{r36} + v_{s36}) \tag{3.82}$$

From the equations 3.81, 3.82, 3.77 and 3.79 the free mobility of the sending structure Y_{s33} for 3rd DoF of excitation and 3rd DoF of response can be determined following the filter network mentioned above.

$$-Z(v_{s36} + v_{r36})Y_{s33} = v_{s36} \tag{3.83}$$

$$F_{s3}Y_{s33} - Z(v_{s35} + v_{r35})Y_{s33} = v_{s35} \tag{3.84}$$

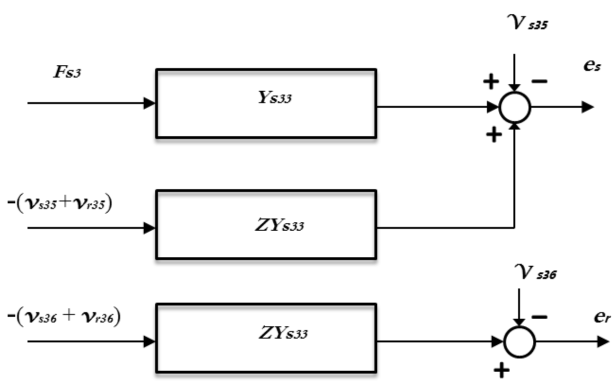

Figure 3.13: Formation of equation as network of filters suitable for the LMS algorithm for Y_{s33}

3.3.6 Comsol Simulation for finding velocities

In Comsol initially 2D space dimension is selected. Then two types of physics are selected 'Beam(beam)' and 'Multibody Dynamics(mbd)'. 'Frequency Domain' study have been done. Then Parameters are set as mentioned in table 3.3 and 3.4.

The drawing of the coupled system is done in comsol.

Table 3.3: Parameters of the Beam

	Values
Young's Modulus	7200 Pa
Isotropic Loss Factor	0.4
Poison's Ratio	0.34
Density	2700 kg/m^2

Table 3.4: Parameters of the Connector

	Values
Spring Constant	100 N/m
Damping Coefficient	0.02 Ns/m

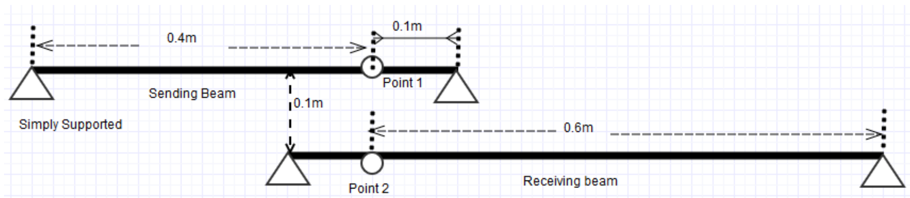

Figure 3.14: Two beams Geometry

'Bezier Polygon' is created which resemble the beams in the system. One is 0.5m and another is 0.7 m long according to the drawing.The upper one is considered as the sending beam and the lower one is the receiving beam. Two beams are 0.1m meter apart. Two points are created on the both beams exactly in the same point 0.4m from the origin. The point 1 is the point in the sending beam and point 2 is in the receiving beam. And depending on the condition the force is added in the point 1 and point 2 respectively. To make the beams simply supported the prescribed displacement in y-direction is taken as 0 at the two end of the beams.

Material properties like Young's Modulus, Isotropic Loss Factor, Poison's Ratio and Density which are chosen as the close to Aluminium. The values are mention in table 3.3.The beam section damping is added as Loss factor model type and Isotropic loss factor value is given 0.02.

Under Multibody Dynamics spring-damper is added into the system. After Spring constant and damping coefficient are set as 3.4, meshing is carried out.

The study is performed within low to mid range frequency (1-2000Hz). The simulation is run for 1-2min. In result section, the data of velocity is taken for point 1 and point 2. For higher degree of freedom, angular velocity data is also taken as a text file format.

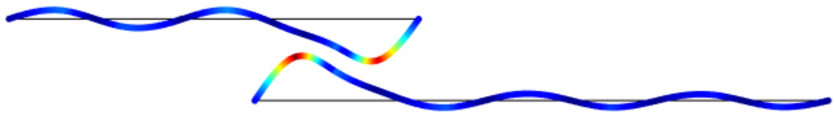

Figure 3.15: Two beams after simulation in Comsol

To convert .txt format. to .mat format the Matlab script readMultiphycis.m is used. Then taking all the frequency response the Matlab script LMS.m is used to take the impulse response and then finding the velocities that were required for the equations above.

4

Results and Discussion

Principle method primarily depends on properties and structural motion responses, the perfect identification of the system properties become difficult. Again noise during the measurement leads to more erroneous results. In this thesis, adaptive algorithm been studied on the basis of comsol simulation on a simply supported aluminum beams[8].

It was assumed that the beam's point-like structure-borne sound source, exciting the assembly in one DoF denoted by Fs. The source is located directly on the sending beam. The vibration responses measured in terms of velocity at one DoF calculated from the receiving beam. Then the same procedure is applied for the 2nd DoF excitation and 2nd DoF response.

Impact testing methods are used to identify the dynamic properties of the system. The obtain frequency response functions (FRF) $H(w) = V(w)/F(w)$ are represented by mobility functions that are the complex ratio of the velocity spectrum V(w) measured at response DoF over the mobility spectrum measured at the source DoF. Alternatively, the principle of reciprocity could be invoked, which allows excitation and response points to be reversed.

As the whole system is reconstructed in the time domain, the impulse response functions (IRFs) is required as system characteristics. Inverse fourier transformation of each frequency response function (FRF) gives the desired IRF. Proper selection of sampling parameters and time windows very important while transforming from frequency domain to time domain to avoid leakage .

One important thing is that to get real-valued impulse response from a complex frequency response the negative frequencies needed to be calculated to get full FRF. In this case, it is done by taking the complex conjugate of the positive FRF and flipping it. As the whole IRF consist of both positive and negative FRF, to reduce the computation time the IRF has been truncated. The square impulse response is used to determine the IRF length.

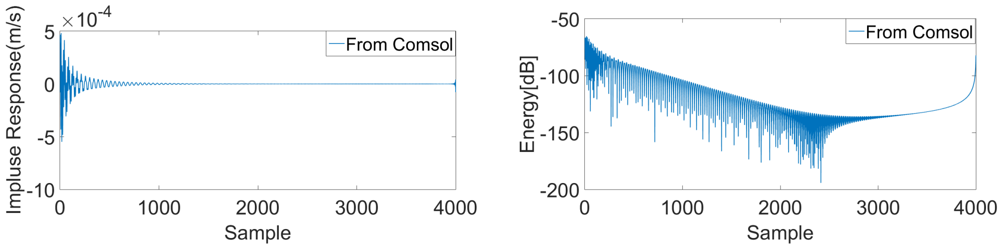

Figure 4.1: Impulse Response and Squared Impulse Response from Comsol according to sample

In this section, the simulation was done for 1st DoF and then 2nd DoF. The velocity data were calculated for different cases. The text files from the comsol were run in the Matlab script readMultiphycis.m (given in the appendix) in order to get .mat files. LMS algorithm was used to predict the impulse response(filter length) and the frequency response(free mobility) of the coupled and uncoupled condition of the beam.

4.1 Comparing results in 1st degree of freedom

Simulations were carried out on a 0.5m and 0.7m simply supported beams. The beam was excited at a certain point with a unit force. The free mobility of the system was calculated. The length N of the excitation force and velocity signal was chosen to be 8192 samples. The length I of the impulse response function is 2048 samples which was chosen from squared impulse response. The sampling frequency was 4000 Hz. An iteration process was implemented in accordance with equation 2.5.

In the Matlab code, two LMS algorithms are used: one to predict the multiplication of the unknown impedance and free mobility (ZYs). And the second one is used with the results from the previous, to predict the free mobility, according to the figure 3.2. The iteration process is stopped depending on the relative error. It is the criteria to judge the convergence of the algorithm. By using equation 2.8 the relative error can be determined. In figure 4.2 showed the relative error as a function of the number of iterations for an estimation. The iteration process is stopped when the error lower than percent 0.1 for the 1st algorithm and $10-6$ percent for the 2nd algorithm is reached. The decaying pattern of both figures also shows that the complete convergence of the system.

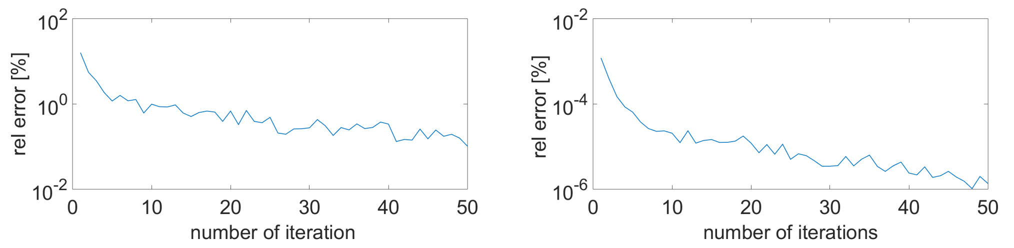

Figure 4.2: Convergence of the error

Figure 4.3 shows two free mobilities of the combined structure, one predicted from the LMS algorithm and the other calculated from Comsol simulation. Here the force was applied in the 1st beam(sending beam) close to one end which is denoted by point 1 in the figure 3.14. The response is taken from the 2nd beam (receiving beam) at a point which is perpendicular to point 1 in the 1st beam. The point in the 2nd beam is denoted by point 2 in figure 3.14. Equation 3.7 and 3.8 are applied in this case. Both graphs follow an almost similar pattern. The two graph and their eigenfrequencies are exactly the same. It was assumed that first eigenfrequency comes from the spring used in the structure while the later ones come from the combined structure.

The absolute error is also shown in the right side of each figure. It is calculated by taking the difference between the logarithmic power of the absolute value of free mobility from comsol and LMS Algorithm prediction. Here, the error is found to be less than 1 dB for the calculated frequency range besides the low-frequency ranges.

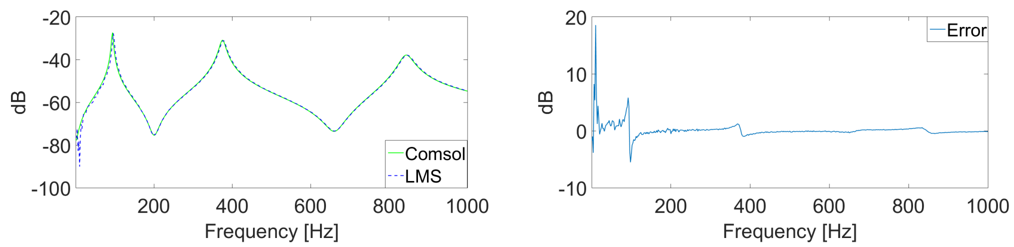

Figure 4.3: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

Again for the free mobility in the receiving beam Yr, the same convergence of the error is checked and is shown in the figure 4.4. It shows that the relative error is decaying as the number of iterations increase.

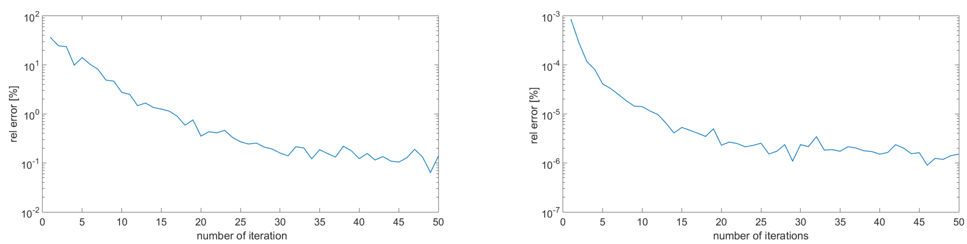

Figure 4.4: Convergence of the error

In figure 4.5 the opposite case is presented where the force is applied to the 2nd beam (receiving beam) at point 2 and the response is taken from the 1st beam (sending beam) at point 1 and vise verse following the equation 3.9 and 3.10. Here the absolute error is less than 1dB in all cases except in the lower frequencies. In lower frequencies (like 0-10 Hz) the error is high but it gradually decreases and at around 100Hz the error is negligible.

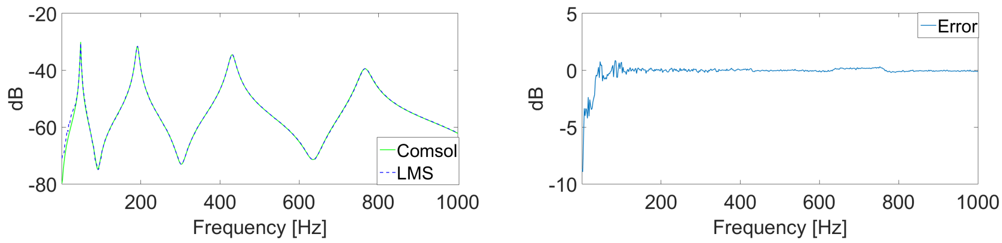

Figure 4.5: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

4.2 Comparing results in 2nd degree of freedom

In section 3.2 it is mentioned that there are eight free mobilities for 4 different cases. Each mobility was calculated in comsol and in the time domain using LMS algorithm.Those are presented as as function of frequency. The difference of both methods are also presented as absolute error. Figure 4.6 shows the free mobility of the sending beam Y_{s11},for case 1 which is mentioned in section 3.2 in method chapter. In this case, both the excitation and the response are taken in 1st DoF. Below 250 Hz some deviation from the comsol simulation is found and but after that, the absolute error becomes close to zero. Again around 800 Hz, some deviation is seen.

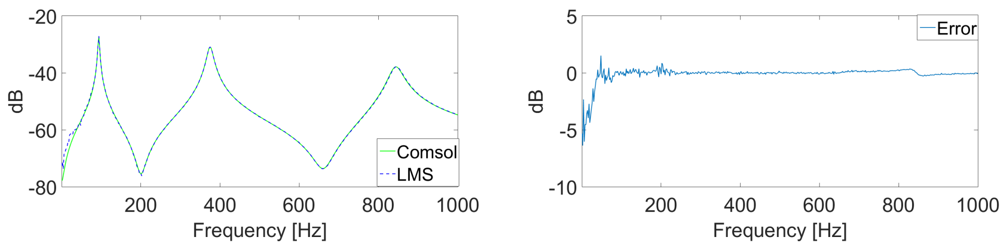

Figure 4.6: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

Figure 4.7 shows the free mobility of the sending beam Y_{s21},for case 2 which is mentioned in section 3.2 in method chapter.The absolute error is less than 1dB above 100 Hz frequency.

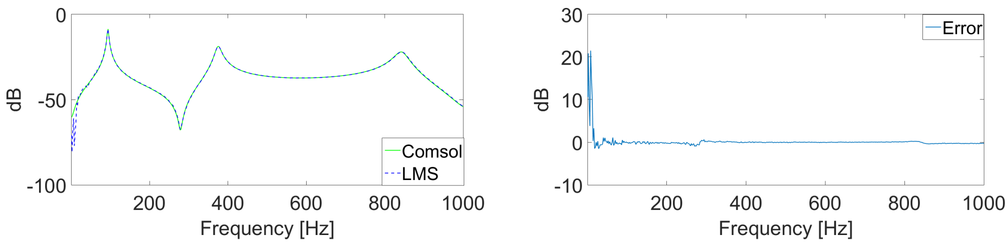

Figure 4.7: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

Figure 4.8 shows the free mobility of the sending beam Y_{s12},for case 3. The absolute error shows the same pattern but it has little deviation around 250 Hz and 800 Hz.

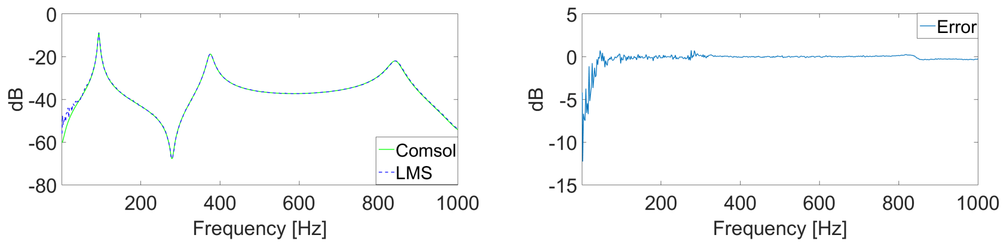

Figure 4.8: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

Figure 4.9 shows the free mobility of the sending beam Y_{s22},for case 4.The absolute error is considerably low.

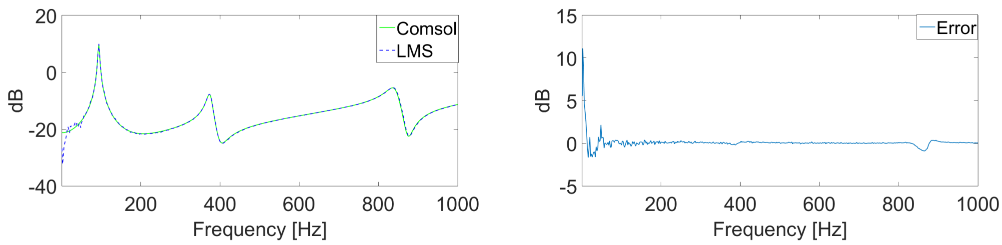

Figure 4.9: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

Now for the description for the receiving structure the four free mobilities Y_{r11}, Y_{r21}, Y_{r12}, Y_{r22} were determined. The procedure is the same as before like determining the free mobilities in the sending structure. But in this case, the equations are constructed in a different way as it mentions in case 3,4 in the method section. Also, the absolute errors will also be calculated in the same fashion.

Figure 4.10 shows the free mobility of the receiving beam Y_{r11},for case 1. The absolute error is more than 5dB in lower frequency and gradually goes to zero.

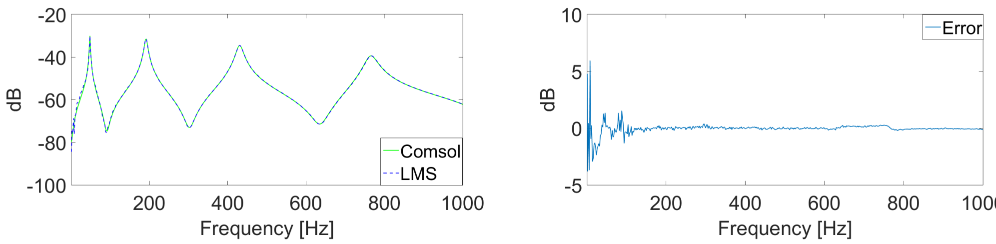

Figure 4.10: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

Figure 4.11 shows the free mobility of the receiving beam Y_{r21},for case 2. The absolute error is more than 10 dB in low frequencies but improved later on.

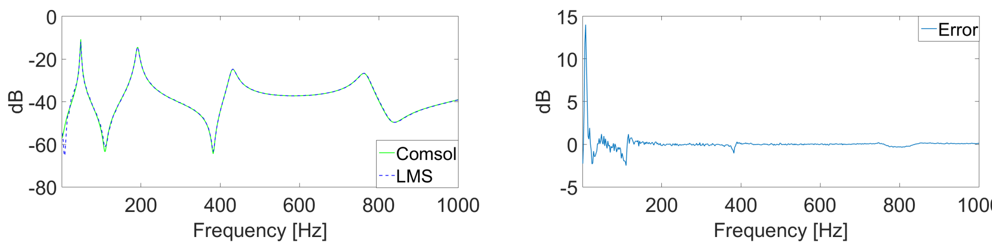

Figure 4.11: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

Fgure 4.12 shows the free mobility of the receiving beam Y_{r12},for case 3. Here is interesting phenomenon is the increase of absolute error(close to 4 dB) around 100 Hz and then it decreases to less than 1 dB. At 800 Hz another deviation is found.

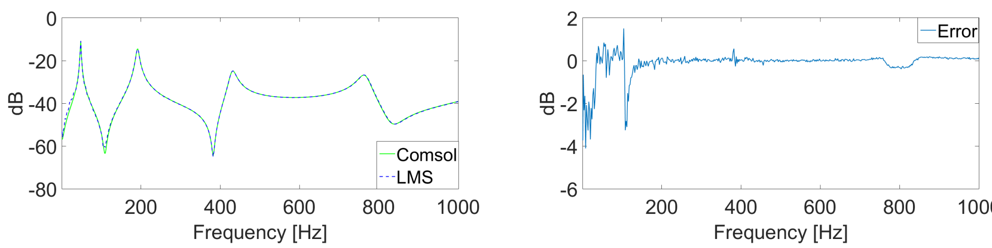

Figure 4.12: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

Figure 4.13 shows the free mobility of the receiving beam Y_{r22},for case 4. At the pick points(150Hz, 400Hz, and 900 Hz) sharp deviation is found in absolute error graph. It might be due to phase shift of two curves.

Table 4.1: Different Spring Constant

	Values
1st case	20000 N/m
2nd case	50000 N/m

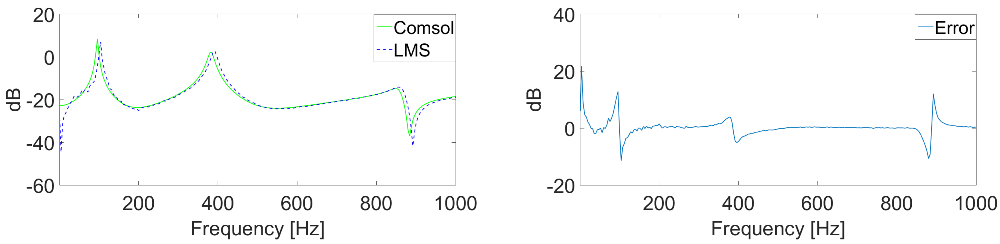

Figure 4.13: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

4.3 Effect of different Spring Constant

The spring constant is a very important parameter that affects the free mobility of the coupled structure. In this experiment, the two beams are connected with a spring. In the beginning, the spring constant is lower(k=100Nm). The force that is transmitted through the coupled spring is less. So the velocity found in the structure is lower. As the spring constant increases the force being transmitted through the spring also increases. It increases the velocity of the structure.

In this section very high spring constant is used to see its effect on the structure. After a number of simulations, it is found that the deviation in free mobility from comsol and LMS algorithm is considerably large when the spring constant is above 5000 Nm. In 20000 Nm spring constant, the deviation is very prominent. In this thesis, the two spring constants are studied which are presented below.

To analyze the effect of spring constant on free mobility, two extreme cases are considered: One mobility of the sending beam for case 1 (section 3.2) where all the excitation and response is taken in 1st DoF and the other mobility of the sending beam for case 4 (section 3.2) where all the excitation and response is taken in 2nd DoF.

For the first case, at 20000 Nm spring constant, the difference between both methods up to 5 dB in lower frequencies (100 Hz) found in figure 4.14. But for higher spring constant at 50000 Nm the deviation is increased up to 10 dB in lower frequencies and even higher frequencies like 400 Hz and 850 Hz some deviation occurs(figure4.15).

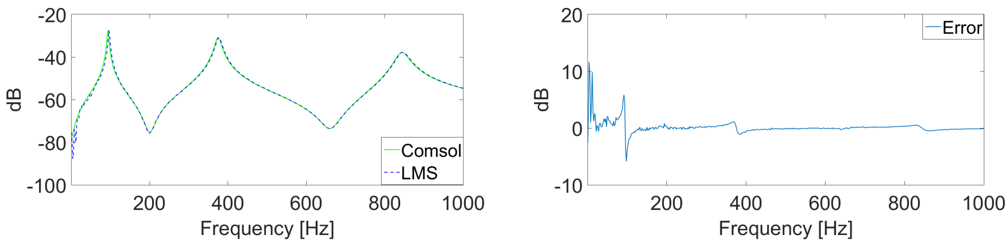

Figure 4.14: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

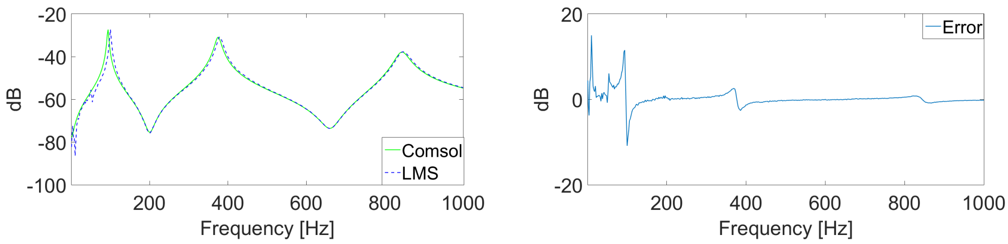

Figure 4.15: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

For the second case at 20000 Nm spring constant, the absolute error is around 10 dB in the pick frequencies(150 Hz, 450 Hz, and 900 Hz) in figure 4.16. And for higher spring constant the error goes up to 20 dB that shown in the figure 4.17

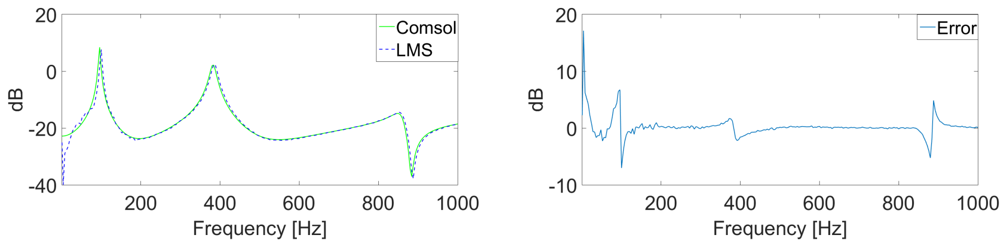

Figure 4.16: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

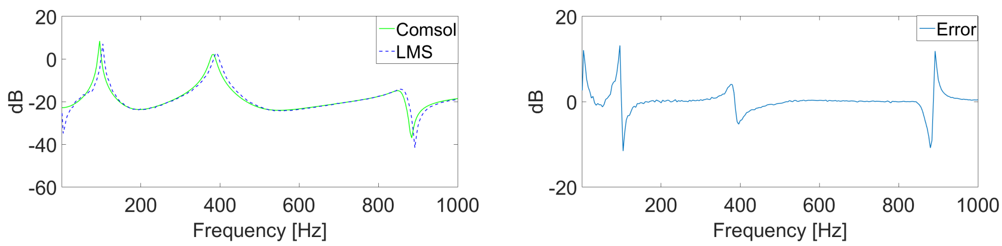

Figure 4.17: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

Table 4.2: Different Isotropic loss factor

	Values
1st case	0.06
2nd case	0.08
3rd case	0.01

For different cases, the same results are found. So it can be concluded that as the spring constant increases it is difficult to predict the free mobility from LMS and it deviated from the simulation data. By increasing the iteration steps the absolute error might be mitigated.

4.4 Effect of different Isotropic loss factor

The isotropic loss factor is a parameter that affects the material damping.In this thesis, it is the parameter of the beam. Material damping transforms the vibration energy of the structure into another form of energy such as heat. As the loss factor goes higher the vibration in the structure will be reduced that also reduced the velocity. Eventually, the amplitude of the free mobility will be decreased.

Here mobility of the sending beam for case 1 (section 3.2) where all the excitation and response is taken in 1st DoF, is chosen to analyze the effect of different isotropic loss factors. Initially, the loss factor is chosen .04. When the isotropic loss factor is .06, in figure4.18 shows that the absolute error in lower frequencies is 30 dB. Then the error reduced and become less than 1 dB in higher frequencies.

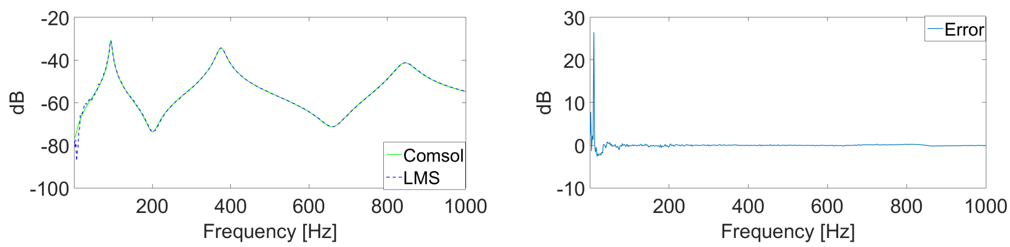

Figure 4.18: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

At isotropic loss factor 0.08, in figure4.19 shows the reduction of the absolute error in lower frequencies up to -15 dB.

Table 4.3: Different Damping Coefficient

	Values
1st case	0.04
2nd case	0.06
3rd case	0.08
4th case	1.00

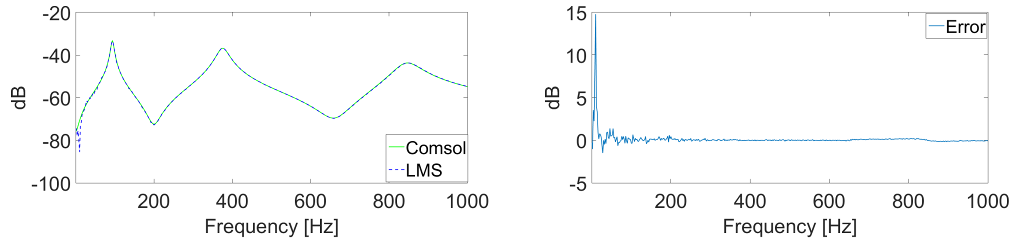

Figure 4.19: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

Figure4.20 shows the reduction of the absolute error in lower frequencies up to -10 dB at isotropic loss factor 0.1.

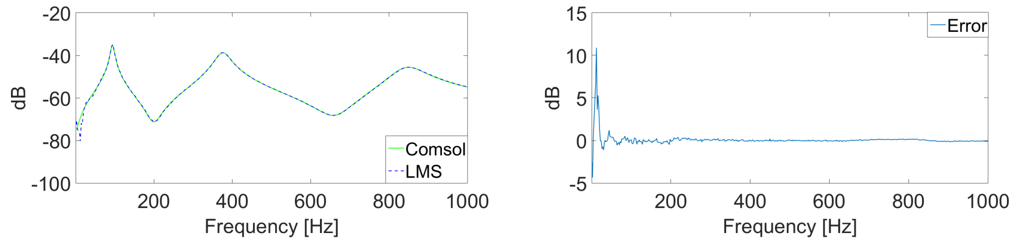

Figure 4.20: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

So it can be concluded that in higher isotropic loss factor the absolute error in lower frequencies reduced considerably. For higher frequency, there is no significant effect.

4.5 Effect of different Damping Coefficient

Damping coefficient is the parameter of the connector that might affect the results. In this case, 4 different damping coefficient was applied here. And the excitation and receiving condition remain same the previous section.

For 1st case, 0.04 damping coefficient was applied. Figure 4.21 shows the same pattern as before some deviation of absolute error in lower frequencies and not much error in higher frequencies.

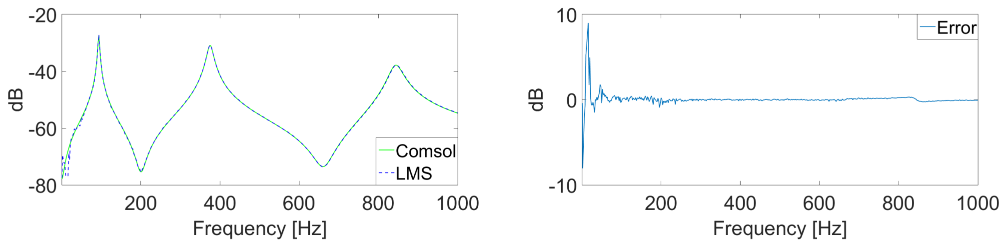

Figure 4.21: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

For 2nd case, the damping coefficient is applied 0.06. For this the absolute error is presented in figure 4.22.

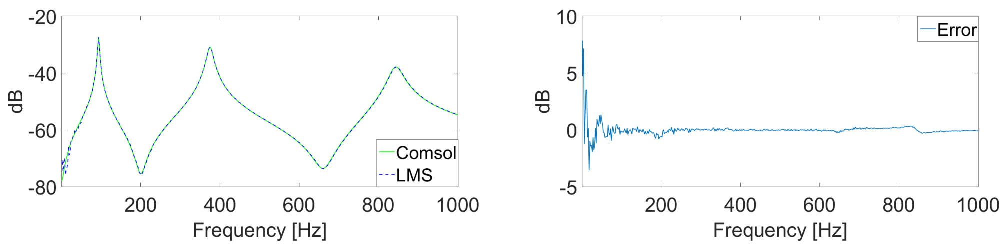

Figure 4.22: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

For 3rd case, the damping coefficient is applied 0.08.For this the absolute error is presented in figure 4.23.

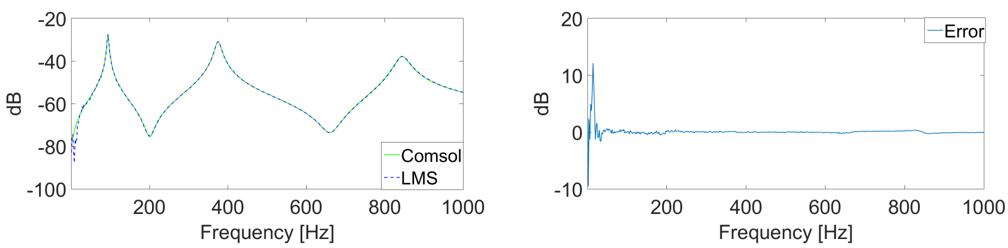

Figure 4.23: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

For 4th case, the damping coefficient is applied 0.1. For this the absolute error is presented in figure 4.24.

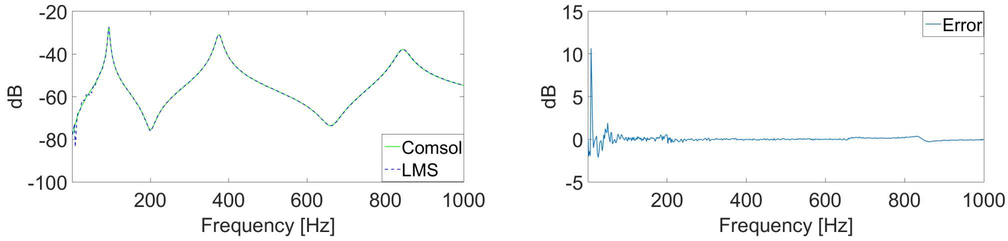

Figure 4.24: Free Mobility predicted from LMS Algorithm and Comsol Simulation and Error of the estimation

It is found that all the graphs show the almost same results. At the end, it can be concluded that due to very low damping coefficient there is not much effect on the results.

5

Conclusion

The LMS algorithm is a common and well-known tool in adaptive design filters. In this thesis, LMS algorithm is used in the time domain and combined with the frequency domain Principle Method to investigate the free mobilities of a coupled structure. Two beams coupled in one degree of freedom and two beams coupled in two degrees of freedom by an elastic mount are the two cases mentioned here. In both the cases, LMS algorithm shows good results.
Some important parameters of the structure and elastic mount that might affect the dynamic system of the structures are also investigated. Among them, structural damping parameter: isotropic loss factor and mounting parameter: spring constant has the most effect. High loss factor and high spring constant increases the error between the simulation data and LMS prediction in low frequencies.

The equation system is programmed as a filter network to identify the solution. The shortcoming of the method is huge calculation time due to the iteration process. If the iteration process increases it can increase the calculation time up to few hours. Another important issue for LMS algorithm is the step size, Small step size gives more accurate results. If the step size is very small it might take a long time to calculate. So an optimal step size should be used to reduce the calculation time without affecting the accuracy of the results.

Further work can be done by increasing the number of DoF of the mounting. Investigate its effect in predicting the free mobility using LMS algorithm. In this thesis, the classical LMS algorithm is used which can be improved to get a better prediction in the higher degree of freedom. For solving the equation system another approach was showed by Wolfgang and Pevic [1].Direct solving with a symbolic toolbox, it might be interesting to analyze the effect of this different solving method.

Using LMS algorithm in structure-borne sound and system and source identification rather than the conventional inverse method is a quite new approach. System properties can be easily identified through this method. Due to the robustness of the solution, it can be a very efficient alternative of understanding the coupled structure without decoupling them.

6
Further Work

The time domain approach of identifying system properties in one and two degrees of freedom opens up a lot of possibilities for further investigations. Four examples are given in the following:

1. In this thesis, the system properties are calculated for one and two degrees of freedom, It can be increased up to six degrees of freedom. It will be interesting to see how the absolute error changes according to the degree of freedom.

2. LMS algorithm used here is the most classical one. There are other types of LMS algorithm like X-LMS can be used to increase the accuracy of the prediction. Using only classic algorithm, a parametric study has been done in this thesis. Next level could be using types algorithm for the parametric study to find the optimal results. Also, different parameters of the algorithm like step size can be altered to see its effect on the final results.

3. In the thesis, for solving the equation the filter network is used and other solving methods like symbolic math toolbox [1] can be used. It was used by Wolfgang and Pevic. This method is used one filter instead of a network of a number of filters. It requires a number of convolutions to simplify the output of the filter. So it might give different results because of too many convolutions in the pre-processing stage.

4. The experimental setup is very important to verify any method. As the simulation and the prediction are really close the next step is to proof the prediction in practical domain.

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A

Appendix 1

A.1 Matlab code for Data collection form Comsol

```
clear variables
close all
clc

% Setup section
% ==============================================================

filename = 'case34.txt';

% Buffer size for reading one line, if you have many freqs you
might need to increase this
buffersize = 120*1e3;                              % bytes

%% ==============================================================

% read data
% ==============================================================

fid = fopen(filename);              % open file

% see if file exists
if fid < 0
  error('File cannot be opened.')
end

% read file as cell array of characters, newline is used
as delimiter (i.e.each line will be one entry in the cell
array), increase buffer to accommodate the long lines. Then
remove outer cell array.
txt_data    = textscan(fid,'%s','Delimiter','\n','BufSize',
buffersize);
txt_data = txt_data{1};
```

```
% close file again
fclose(fid);

% number of read lines
num_lines = length(txt_data);

%% ==================================================================

% Go through header data to find
%       * number of dimensions (number of coordinates),
%       * number of nodes,
%       * length of data,
%       * and description string.
% Also get indice of description line as this is the last
before the data starts.
% ==================================================================

for ii=1:num_lines
  if strfind(txt_data{ii},'Dimension')
    [~,dim_str] = strtok(txt_data{ii},':');
    % split line at :
    dim_str      = regexprep(dim_str,'^:[  ]+','');
    % remove leading ':' and whitespace in reminder
    num_coords     = str2double(dim_str);
  elseif strfind(txt_data{ii},'Nodes')
    [~,node_str] = strtok(txt_data{ii},':');
    % split line at :
    node_str      = regexprep(node_str,'^:[  ]+','');
    % remove leading ':' and whitespace in reminder
    num_nodes     = str2double(node_str);
  elseif strfind(txt_data{ii},'Expressions')
    [~,length_str] = strtok(txt_data{ii},':');
    % split line at :
    length_str      = regexprep(length_str,'^:[  ]+','');
    % remove leading ':' and whitespace in reminder
    data_length     = str2double(length_str);
  elseif strfind(txt_data{ii},'Description')
    [~,desc_str]   = strtok(txt_data{ii},':');
    % split line at :
    desc_str       = regexprep(desc_str,'^:[  ]+','');
% remove leading ':' and whitespace in reminder

    % Multiphysics 4.3a adds another line after description
    to the txt
    if strfind(txt_data{ii+1},'Length unit')
      [~,coord_unit_str]   = strtok(txt_data{ii+1},':');
```

```
% split line at :
      coord_unit_str       = regexprep(coord_unit_str,'^:[ ]+','');
% remove leading ':' and whitespace in reminder
      last_dec_line = ii+1;
    else
      last_dec_line = ii;
    end
    break
  end
end

%% ==========================================================

% Next line after description line: Contains info about
the coordinates and the frequencies
% ==========================================================

var_line = txt_data{last_dec_line+1};

% determine coordinate names and setup array
coord_str = char(regexp(var_line,'( x  )|( y  )|( z  )','match'));
% extract
coord_str   = strrep(coord_str(:).',' ','');
% remove whitespace
coordinates = zeros(num_nodes,num_coords);
% array for storage of coordinate values

% determine name of stored data
data_name  = char(regexp(var_line,'[*a-z]+[ ]\([*a-z]\)',
'match','once'));
data        = zeros(num_nodes,data_length);
% array for storage of coordinate values

% prepare frequency extraction
f           = zeros(1,data_length);
freq_count = 1;

% read freq data
% Maybe not most elegant approach: Line is converted to cell
array, we loop to all entries and store the numerical part
of those containing 'freq=123'
freq_str = textscan(var_line,'%s');
freq_str = freq_str{1};

for ii=1:length(freq_str)
  if strfind(freq_str{ii},'freq=')
```

```
    f(freq_count) = str2double(strrep(freq_str{ii},'freq=',''));
    freq_count     = freq_count+1;
  end
end

%% =====================================================================

% Read all data
% Quite easy as these lines only contain numbers. We simply
extract the coordinates, the rest has to be data.
% ======================================================================

% loop over all data lines
for ii=1:num_nodes
  data_line          = str2num(txt_data{last_dec_line+ii+1});
  %#ok<ST2NM>
  coordinates(ii,:)  = data_line(1:num_coords);
  data(ii,:)         = data_line(num_coords+1:end);
end

%% =====================================================================

% Save data as matlab file
% =====================================================================

% try to remove txt ending from original filename and add .mat
savename = [strrep(filename,'txt','') 'mat'];

if exist(coord_unit_str)==1
  save(savename,'f','coordinates','data','coord_str','desc_str',
  'data_name');
else
  save(savename,'f','coordinates','data','coord_str','desc_str',
  'data_name','coord_unit_str');
end
```

A.2 Matlab code for 1 DoF and 2 DoF Coupling

```
% "Structure-borne sound characterization of structures in coupled
% conditions applying a time domain approach" by Wolfgang Kroop and
% Goran Pavic published in inter.noise 2015, San francisco
% California USA

% Using the princepal method in the time domain
% LMS algorithm is used here to predict unknown force
```

```
    clear all
    close all
    clc

    %% files for all the cases
    a = load('case5.mat');
    b = load('case6.mat');
    c = load('case9.mat');
    d = load('case10.mat');
    e = load('case33.mat');

    L = 500;
    y = L;
    iter = 0    ; % iteration for the LMS
    % estH = zeros(1,y);
while iter < 50;
    iter=iter+1;

    force = rand(1,10000)-0.1;                 % force applied to the
                                               % structure
    Vsr = conv(b.IR(1:2000),force);            % velocity at
    % Vsr = filter(b.IR,1,force);              % receiving structure
    Vrr = conv(d.IR(1:2000),force);            % velocity at
    % Vrr = filter(d.IR,1,force);              % receiving structure

    input = -(Vsr+Vrr);                        % total input signal



    x = y;
    desired_output = -Vsr;                     % desired output
signal
    iteration = 10000;                         % iterations for LMS
    error = zeros(size(input));                % initial error
    min_error = 1e-12;                         % Minimum error expectable

    alpha_max = 1./(L.*mean(input.^2));        % maximum step size
    alpha = 5e-1*alpha_max;                    % Actual step size

    error(1:y) = desired_output(1:y);          % initial error

    filter_coef = zeros(iteration , y);        % filter coefficient
    if iter ~= 1
        filter_coef(x,:)= filter_coef_final(iter -1,:);
    end
    filter_output = zeros(size(input));        % filter output
```

```
    noiseamp = 0.0178;

    while  (abs((error(x-1)/desired_output(x-1))*100) > 0.0000001)
    &&(x < iteration)
        filter_output(x)=filter_coef(x,:)*input(x:-1:x-y+1)';
        error(x)= desired_output(x)- filter_output(x);
        filter_coef(x+1,:) = filter_coef(x,:)
        +alpha*error(x)*input(x:-1:x-y+1);
        x=x+1;
    end
%     plot(error)
    filter_coef_final(iter,:) = filter_coef(end,:);

end
  %% 2nd step of lms
     A = mean(filter_coef_final);
     iter2=0;
while iter2 < 50

    iter2= iter2+1;
    Vss = conv(a.IR(1:2000),force);              % velocity at
   % Vss = filter(a.IR,1,force);                 % receiving structure

    Vrs = conv(c.IR(1:2000),force);              % velocity at
   % Vrs = filter(c.IR,1,force);                 % receiving structure


    input_filter=-(Vss+Vrs);
    desired_1st=conv(input_filter, A);
    desired_2nd=Vss;
    desired_total=desired_1st(length(desired_2nd))-desired_2nd;

    input_final=force;

    L_2nd=500;
    p=L_2nd;
    q=p;

    error_2nd = zeros(size(input_final));                % initial error


    alpha_max_2nd = 1./(L_2nd.*mean(input_final.^2));   % maximum
                                                         % step size
    alpha_2nd = alpha_max_2nd;

    error_2nd(1:p)= desired_total(1:p);
```

```
    filter_coef_2nd = zeros(iteration , p);                % filter
                                                           % coefficient
    if iter2 ~= 1
           filter_coef_2nd(q,:)= filter_coef_2nd_final(iter2 -1 ,:);
    end

    filter_output_2nd = zeros(size(input_final));          % filter output

      while  (abs((error_2nd(q-1)/desired_total(q-1))*100) > 0.0000001)
      &&(q < iteration)
         filter_output_2nd(q)=filter_coef_2nd(q,:)*
         input_final(q:-1:q-p+1)';
         error_2nd(q)= desired_total(q)- filter_output_2nd(q);
         filter_coef_2nd(q+1,:) = filter_coef_2nd(q,:)
         +alpha_2nd*error_2nd(q)*input_final(q:-1:q-p+1);
         q=q+1;
      end

  filter_coef_2nd_final(iter2,:)= filter_coef_2nd (end,:);
end
    B=mean( filter_coef_2nd_final);
    W=e.IR;

    mobility_old=fft(B);
    mobility_LMS=mobility_old*2;

    % Fs = length(a.FR)*(force(2)-force(1));
    % N=length(mobility_old);
    % df=(force(2)-force(1))*Fs/N;
    N=24000;

    df=N/length(mobility_LMS)/2;

    fre_axis=0:df:(length(mobility_LMS)-1)*df;

    mobility_C_old=fft(W);
    mobility_comsol=mobility_C_old*2;


    % Fs1 = length(e.FR)*(force(2)-force(1));
    % N1=length(mobility_C_old);
    % df1=(force(2)-force(1))*Fs1/N1;
    N1=24000;

    df1=N1/length(mobility_comsol)/2;
```

```
fre_axis1=0:df1:(length(mobility_comsol)-1)*df1;



figure (1)
semilogx(fre_axis1,20*log10 (abs(mobility_comsol)))

hold on
semilogx(fre_axis,20*log10 (abs(mobility_LMS)))

xlim([1 5000]);
title('Free Mobility from Experiment','FontSize',20)
xlabel('frequency (Hz)','FontSize',20)
ylabel('Mobility', 'FontSize',20)
legend('Mobility Comsol','Mobility LMS','Location','north')
set(gca,'FontSize',20)

figure (2)
plot(error) ;
title('Error curve for 1st LMS') ;
xlabel('Samples');
xlim([0 iteration])
ylabel('Error value');

figure (3)
plot(error_2nd) ;
title('Error curve for 2nd LMS') ;
xlabel('Samples');
xlim([0 iteration])
ylabel('Error value');
```