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by

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Abstract

The focus of this thesis is developing alternate methods for comparing various fully trimmed vehicle body structures. Traditionally, experimental modal analysis has been used to achieve this, but has seen limited success. The challenge is developing global trends using information from very distinct points. This thesis examines the use of single input and multi-input transmissibility as measured on a four post road simulator as an alternate means to compare similar or dissimilar vehicle structures.

Early work with transmissibility indicated some differences in vehicle structures, but suffered from some of the same problems as experimental modal analysis techniques. A group transmissibility concept was developed in a parallel thesis[1], but the most promising work focused on use of principal component analysis (PCA) to reduce large amounts of data to a smaller set of representative data. Principal Component Analysis (PCA) methods have been variously developed and applied within the experimental modal and structural dynamics community for some time. While historically the use of these techniques has been restricted to the areas of model order determination utilizing the complex mode indicator function (CMIF), enhanced frequency response function (eFRF) and virtual response function estimation, and parameter identification, increasingly the PCA methodology is being applied to the areas of test/model validation, experimental model correlation/repeatability and experimental/structural model comparison. With the increasing volume of data being collected today, techniques which provide effective extraction of the significant data features for quick, easy comparison are essential. This thesis also explores the general development and application of PCA to transmissibility measurements and the ability of PCA to provide the analyst with an effective global trend visualization tool.
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Chapter 1. Introduction

1.1 Motivation

In the field of automotive research, one recurring concern is cabin noise and vibration. Cabin noise and vibration can contribute to customer perceived quality problems traditionally described as noise, vibration, and harshness (NVH).

Traditionally, engineers have used frequency response functions (FRFs) and modal analysis to quantify the vibration in automotive structures. These methods provide very accurate results, but these results are specific to the vehicle tested and therefore difficult to compare to similar vehicles with different structural sizes and configurations.

During the development process, vehicles are frequently tested on a four axis road simulator for durability, NVH, and other quality considerations. Because of this, a structural test that takes advantage of this type of test and test system is attractive. Additionally, four axis road simulators contain linear variable displacement transducers (LVDT) which can be utilized to quantify the input to the system in terms of displacement. This makes the measurement of vehicle response to motion inputs a convenient way to describe the response of the vehicle to the excitation. While the input force(s) can be measured, via load cells at each axis, this instrumentation is not common, is very expensive, and is not available at the University of Cincinnati, Structural Dynamics Research Lab (UC-SDRL).

Transmissibility traditionally refers to the ratio of the force transmitted to the foundation ($F_T$) referenced to the equivalent or driving force ($F_{EQ}$)[2]. Equivalently, for a moving base, transmissibility can be described as the ratio of displacement of the structure to the displacement of its base. These two applications are described by the same relationship (equation) between the
mass, damping and stiffness of a single degree of freedom (SDOF) system. Transmissibility, for this SDOF example, emphasizes the structure motion and reduces the influence or dominance of the natural frequencies. While transmissibility is normally defined as a single input, single output, SDOF concept, to take advantage the four axes in a four axis road simulator, one must use a multiple input, multiple output (MIMO) approach, involving MDOFs, to provide a definition of transmissibility for realistic structural systems. For the case of the four axis road simulator, since the displacements are readily available in each of the four hydraulic actuators (utilizing internal linear, variable, differential transformer (LVDT) sensors), the motion transmissibility at various locations on the automotive structure can be easily estimated with respect to the four LVDT displacements. With respect to utilizing a four axis road simulator to control the four inputs, conditions must be placed on the four inputs to permit numerical estimation of MIMO transmissibility, much in the same way that MIMO FRF is estimated.

1.2 Literature Review

This thesis is focused on several topics relative to experimental evaluation of automotive structures. The first topic is finding an experimental method that allows dissimilar structures to be compared. Experimental modal analysis is useful for comparing identical structures. One of the goals of this thesis is to determine if transmissibility will be useful in comparing similar but not identical automotive structures. While much has been written about force transmissibility and displacement transmissibility for SDOF systems, this thesis requires a generalized approach to defining and utilizing displacement transmissibility for a MDOF system in the presence of multiple inputs and outputs. The development of displacement transmissibility for MDOF systems is a straight-forward extrapolation of MIMO frequency response functions (FRFs) that
was initially developed by Bendat and Piersol in 1971 [3] and proven experimentally by Allemang in 1979 [4]. This development is presented in Chapter 2. No specific development of MIMO transmissibility has been found in the literature other than that presented in the MS Thesis by Abbey Yee[1], who is a colleague on this project. Some discussion of the use response transmissibility for nonlinear system analysis is documented in the MS Thesis by Haroon [33] but this has no direct bearing on the content of this thesis.

The other major topic that became a focus for this thesis is, once measured transmissibilities are available for multiple automotive structures, how can the data be evaluated to contrast and compare different structures. Yee, in her MS Thesis, used direct comparison of transmissibilities, from similar locations in different structures, and group transmissibilities, involving averaged transmissibilities in similar regions of different structures, to make these evaluations. While this approach did highlight some of the changes, a different method based upon singular value decomposition (SVD) was found to be more suitable, in that the SVD captures the dominant characteristics from a large amount of data.

Singular value decomposition (SVD) and the associated principal component analysis (PCA) have been found to be very useful mathematical tools in other areas of structural dynamics. The PCA techniques were first developed in the early 1900s but did not come into common use in structural dynamics until the 1970s and 1980s as documented by Jolliffe [5], Deprettere [6], and others. The application of PCA to structural dynamics (and automotive examples in particular) is highlighted in an International Modal Analysis Conference (IMAC) paper by Allemang, Phillips, and Allemang [7] and presented in some detail in Chapter 4.
1.3 Thesis Structure and Content

In Chapter 2, transmissibility is introduced and the development of the MIMO transmissibility function (which parallels the frequency response function) is documented.

Chapter 3 begins with a description of the test setup and application. It proceeds to documents the 20 degree of freedom (DOF) model of the road simulator with automotive vehicle and discusses some of the resulting analysis. This model became a requirement when the restraint straps, that hold the vehicle on the road simulator, broke during the testing of Vehicle D. The final portion of Chapter 3 details the application of the transmissibility function to four axis road simulator test data for multiple fully trimmed vehicles.

The concept of principal component analysis (PCA) is introduced in Chapter 4. It shows the application of PCA to transmissibility data developed in Chapter 3.

Chapter 6 gives conclusions based upon the current work and recommendations for future work. Appendices give background material and scripts that document portions of the work.
Chapter 2. Transmissibility: Theory and Background

2.1 Introduction

The goal of this work is to utilize a four axis road simulator to compare structural characteristics of various vehicles in relation to noise, vibration, and harshness (NVH). This methodology could then be used to compare a given vehicle’s characteristics to best in class target vehicles.

A conventional approach would begin with FRF measurements. From these measurements, modal parameters, including complex natural frequencies ($\lambda$), modal scaling such as modal mass ($M_r$), and scaled modal vector {$\Psi$}, can be determined [8]. These modal parameters can then be compared among vehicles.

The problems with this approach are numerous. FRF measurement on a four axis simulator is difficult and costly to measure directly. While indirect measurement of FRFs, using the actuator pressure and wheel plate motion, for example, is possible, it has proven difficult to generate accurate results and no successful application of measuring FRFs on a road simulator has been found. After FRF measurements are made and modal parameters are estimated, the data still must be compared between vehicles. This process can be difficult due to varying geometries from vehicle to vehicle.
2.2 Traditional Transmissibility (SISO, SDOF)

Given these difficulties, one must examine other methods for comparing vehicle dynamics. Readily available data includes input displacement to each wheel pan and the pressures in each post (hydraulic cylinder) used to impart this displacement. Other measurements that could be easily added include acceleration and input force if appropriate sensors are available. In the UC-SDRL, the latter option was not available and would have been cost prohibitive to acquire.

Given the available sensors, a transmissibility measurement becomes a realizable and desirable way to describe vehicle dynamics. Transmissibility traditionally refers to the ratio of the force transmitted to the foundation ($F_T$) and the equivalent or driving force ($F_{EQ}$)[2]. This is traditionally described for a single degree-of-freedom (SDOF) concept using a single input, single output (SISO) model where motion of the base was assumed to be zero. For this case, the transmissibility (force transmissibility) relationship is:

$$T(\omega) = \frac{F_T(\omega)}{F_{EQ}(\omega)}$$ (1.)

Where:

$$F_{EQ}(\omega) = F_2(\omega) = X_2(\omega) \times (-M_2 \omega^2 + j \omega C + K)$$ (2.)

$$F_T(\omega) = F_1(\omega) = X_2(\omega) \times (j \omega C + K)$$ (3.)

Equation (1.), after substituting and rearranging, can be written as:

$$T(\omega) = \frac{j \omega C + K}{-M_2 \omega^2 + j \omega C + K}$$ (4.)
Figure 1: Transmissibility Model

The above formulation assumes a stationary foundation. In the case where there is motion of both the mass and the foundation, both relative and absolute motions are of interest. Applying Newton’s 2nd Law of Motion to the mass (M₂), results in:

\[ M_2 \ddot{x}_2 = -k(x_2 - x_1) - c(\dot{x}_2 - \dot{x}_1) \]  \hspace{1cm} (5.)

This can be written in the frequency domain as:

\[ X_2(\omega) * (-M_2 \omega^2 + j \omega C + K) = X_1(\omega) * (j \omega C + K) \]  \hspace{1cm} (6.)

Or:

\[ \frac{X_2(\omega)}{X_1(\omega)} = \frac{j \omega C + K}{-M_2 \omega^2 + j \omega C + K} \]  \hspace{1cm} (7.)

Note that this equation, sometimes defined as motion or response transmissibility, is identical to the equation for force transmissibility in Equation (4).

\[ T_{21}(\omega) = \frac{F_1(\omega)}{F_2(\omega)} = \frac{X_2(\omega)}{X_1(\omega)} \]  \hspace{1cm} (8.)
Note that the numerator in the transmissibility equation contains terms that are in the denominator (characteristic equation) and, as such, offset the strong influence of the natural frequency in the transmissibility function. As such, the resulting transmissibility measurement is less sensitive to the natural frequency. Since this application of transmissibility is for relative comparisons, this is not a concern and may be of some benefit when comparing structural similarity; however, this issue needs further study.

### 2.3 Multi-Reference Transmissibility Theory (MIMO, MDOF)

A multi-reference transmissibility can be defined in terms of frequency response functions if frequency response functions are available, either theoretically or experimentally. The definition of the ratio of responses as a transmissibility measurement (motion transmissibility) for the SDOF case is the basis for the development and application of the MIMO transmissibility concept for the four axis road simulator. This MIMO transmissibility concept uses the four wheel pan displacements, measured with internal LVDTs, as simultaneous moving base inputs (references), to outputs (responses) taken at a large number of measurement locations, measured with externally applied accelerometers.

When analyzing a single post of the four axis road simulator, it is reasonable to view the vehicle system as a system attached to a moving support (Figure 1). In that case, the traditional transmissibility relationship is normally formulated using an equivalent force concept where the resulting motion ratio ends up being the same ratio as in the equation above.
Theoretically, the Frequency Response Function matrix is defined as:

\[ [H(\omega)] = [-[M] \omega^2 + j \omega [C] + [K]]^{-1} \quad (9.) \]

Where:

\[ H_{pq}(\omega) = \frac{X_p(\omega)}{F_q(\omega)} \quad \text{and} \quad H_{qq}(\omega) = \frac{X_q(\omega)}{F_q(\omega)} \quad (10.) \]

Using the ratio of the FRF for a given point to the FRF for the associated driving point (at each of the wheel pans), one can define a theoretical transmissibility for the MIMO case as:

\[ T_{pq}(\omega) = \frac{X_p}{X_q} = \frac{H_{pq}}{H_{qq}} \quad (11.) \]

In the above equation, there will be one \( H_{qq} \) for each axis of the four axis road simulator (\( H_{11}, H_{22}, H_{33}, H_{44} \)). This approach is used in Chapter 3 in the development of transmissibility for a 20 DOF model of the road simulator with attached vehicle. However, in the four axis road simulator case, the FRFs cannot be measured unless expensive load plates are added to each wheel pan. This is not available in the UC-SDRL facility and thus an alternative, experimental method for the estimation of transmissibility is formulated in the next section.
2.4 Multi-Reference Transmissibility Measurement (MIMO, MDOF)

The MIMO multi-reference transmissibility model for measurement estimation is unique in terms of each output since the outputs (responses) are not coupled in any way. The following development of the MIMO multi-reference transmissibility exactly parallels the development of the MIMO FRF estimation algorithms [4][9][8]. The MIMO equation for transmissibility can be solved for N_o outputs either as a matrix solution involving all of the outputs or one output at a time as a function of computer memory and speed.

2.4.1 Transmissibility Function Estimation

The following schematic (Figure 2) is representative of the multi-reference transmissibility as a general case.

Figure 2: Multiple Input Transmissibility Measurement Model
The following equation represents the transmissibility measurement case involving multiple references and a single output. This linear equation is simply replicated for each additional output.

\[ \hat{X}_p - \eta_p = \sum_{q=1}^{4} T_{pq} \times (\hat{R}_q - \nu_q) \]  

(12.)

Where:

- \( R = \hat{R} - \nu \)  Actual Input (Reference)
- \( X = \hat{X} - \eta \)  Actual Output
- \( \hat{X}_p \)  Spectrum of p-th output, measured
- \( \hat{R}_q \)  Spectrum of q-th reference, measured
- \( T_{pq} \)  Transmissibility function of output p with respect to reference q
- \( \nu_p \)  Spectrum of the noise portion of the reference
- \( \eta_p \)  Spectrum of the noise portion of the output
2.4.2 Transmissibility Function Estimation Models

The following nomenclature will be used to define the MIMO transmissibility measurement case for the least squares estimation of transmissibility, exactly paralleling the least squares estimation of MIMO frequency response functions [8]:

\[
[G_{XR}] = \{X\}{R}^H = \text{Output-Reference Cross Spectra Matrix}
\]

\[
[G_{XR}] = \begin{bmatrix}
X_1 \\
X_2 \\
\vdots \\
X_{N_o}
\end{bmatrix}
\begin{bmatrix}
R_{11} & R_{12}^* & \cdots & R_{1N_r}^* \\
R_{21} & R_{22}^* & \cdots & R_{2N_r}^* \\
\vdots & \vdots & \ddots & \vdots \\
R_{N_o1} & R_{N_o2}^* & \cdots & R_{N_oN_r}^*
\end{bmatrix}
\]

(13.)

\[
[G_{XR}] = \begin{bmatrix}
G_{XR_{11}} & G_{XR_{1N_r}} & \cdots & \\
G_{XR_{N_o1}} & G_{XR_{N_o2}} & \cdots & \\
\vdots & \vdots & \ddots & \\
\end{bmatrix}
\]

\[
R^* = \text{Complex Conjugate}
\]

\[
[G_{XX}] = \{X\}{X}^H = \text{Output-Output Cross Spectra Matrix}
\]

\[
[G_{XX}] = \begin{bmatrix}
X_1 \\
X_2 \\
\vdots \\
X_{N_o}
\end{bmatrix}
\begin{bmatrix}
X_{11} & X_{12}^* & \cdots & X_{1N_o}^* \\
X_{21} & X_{22}^* & \cdots & X_{2N_o}^* \\
\vdots & \vdots & \ddots & \vdots \\
X_{N_o1} & X_{N_o2}^* & \cdots & X_{N_oN_o}^*
\end{bmatrix}
\]

(14.)

\[
[G_{XX}] = \begin{bmatrix}
G_{XX_{11}} & G_{XX_{1N_o}} & \cdots & \\
G_{XX_{N_o1}} & G_{XX_{N_o2}} & \cdots & \\
\vdots & \vdots & \ddots & \\
\end{bmatrix}
\]

\[
G_{XX_{ik}} = G_{XX_{ik}}^* (\text{Hermitian Matrix})
\]
\[ [G_{RR}] = \{R\}\{R\}^H = \text{Reference-Reference Cross Spectra Matrix} \]

\[
[G_{RR}] = \begin{pmatrix}
  R_1 \\
  R_2 \\
  \vdots \\
  R_{N_r}
\end{pmatrix}
\begin{pmatrix}
  R_1^* & R_2^* & \cdots & R_{N_r}^*
\end{pmatrix}
\]

\[ G_{RR_{ik}} = G_{RR_{ik}}^* \text{(Hermitian Matrix)} \]  

Note that the subscript ‘R’ in the matrixes above refers to ‘reference’ and is not to be confused with ‘response’. Outputs (responses) are denoted with subscript ‘X’. The \( G_{RR} \) matrix is analogous to the \( G_{FF} \) matrix in FRF estimation. As with the \( G_{FF} \) matrix, the \( G_{RR} \) matrix must be invertible for the transmissibility to be computed for the MIMO case. For two or more references, a principal response analysis using singular value or eigenvalue decomposition of the \( G_{RR} \) matrix is needed to determine that the inputs are not highly correlated. Since four axis road simulators, in normal ride simulation use, do not have criteria that require the use of uncorrelated inputs, this is especially important when a unique estimate of MIMO transmissibility is desired. The important point is that standard ride files for random inputs used for vehicle road simulation, in general, cannot be used for the estimation of MIMO transmissibility. This particularity will be examined more in depth in Chapter 3. This computation parallels the principal force (virtual force) computation for MIMO FRF estimation and is used in the same way. For the case of four input transmissibility, this is referred to as principal reference (or virtual reference) analysis. A sample plot from the vehicle testing is shown in Figure 3. Note that this figure shows a case where all four shakers are active, but there are only three independent excitations within the four
excitation drive signals. This measurement case involved the utilization of a typical road simulation ride/drive file which should not be used for MIMO transmissibility estimation.

![Figure 3: Virtual References for Vehicle A (Belgian Block Drive File)](image)

Just as in the MIMO, least squares, FRF estimation process, there are a number of least squares solutions that are commonly used ($H_1$, $H_2$, $H_v$) [9] [8]. For simplicity, the same notation will be used for transmissibility. $T_1$ will refer to the case where the noise on the output (response motion) is minimized, $T_2$ will refer to the case where the noise on the input (reference motion) is minimized and $T_v$ will refer to the case where the noise on the input (reference motion) and the noise on the output (response motion) is minimized in a vector sense.
T₁ Technique:

\[
[T]_{N₀×4} \{R\}_{N_r×1} = \{X\}_{N₀×1} - \{η\}_{N₀×1} \tag{16.}
\]

\[
[T]\{R\}{R}^H = \{X\}{R}^H - \{η\}{R}^H \tag{17.}
\]

\[
[T]_{N₀×N_r} \{R\}_{N_r×1} {R}^H_{1×N_r} = \{X\}_{N₀×1} {R}^H_{1×N_r} \tag{18.}
\]

\[
[T][G_{RR}] = [G_{XR}] \tag{19.}
\]

\[
[T] = [G_{XR}][G_{RR}]^{-1} \tag{20.}
\]

Where:

- \([\ ]^H\) = Complex conjugate transpose (Hermitian)
- \([T]\) = Transmissibility Function Matrix

The above development for T₁ exactly parallels the estimation of FRF using the H₁ algorithm approach.
T₂ Technique:

\[
[T]_{N_o \times N_r} \{(R)_{N_r \times 1} - \{v\}_{N_r \times 1}\} = \{X\}_{N_o \times 1} \quad (21.)
\]

\[
[T] \{(R) - \{v\} \} \{X\}^H = \{X\} \{X\}^H \quad (22.)
\]

\[
[T]_{N_o \times N_r} \{(R)_{N_r \times 1} \{X\}^H\}_{1 \times N_o} = \{X\}_{N_o \times 1} \{X\}^H_{1 \times N_o} \quad (23.)
\]

Solution for \([T]\) can only be found directly using an inverse when number of references \(N_r\) equals number of outputs \(N_o\).

\[
[T] [G_{RX}] = [G_{XX}] \quad (24.)
\]

\[
[T] = [G_{XX}] [G_{RX}]^{-1} \quad (25.)
\]

The above development for \(T_2\) exactly parallels the estimation of FRF using the \(H_2\) algorithm approach.

Tᵥ Technique:

\[
[T]_{N_o \times N_r} \{(R)_{N_r \times 1} - \{v\}_{N_r \times 1}\} = \{X\}_{N_o \times 1} - \{\eta\}_{N_o \times 1} \quad (26.)
\]

The above development for \(T_\nu\) exactly parallels the estimation of FRF using the \(H_\nu\) algorithm approach. This solution involves solving an eigenvalue problem at each frequency. The eigenvalue problem is of size four by four, based upon the four axis road simulator application that has four input references. This approach was not used in the thesis but is
mentioned here for completeness. For more information, please see the MIMO FRF development for the details of the eigenvalue solution approach[9] [8].

The T\textsubscript{1} algorithm approach is the only approach used for the estimation of transmissibility for this thesis. In general, for all three techniques, the four inputs (references) used in the four axis road simulator must not be highly correlated. This means that the actual measured motions at the four hydraulic actuators can be partially correlated but must not be completely correlated at any frequency in the analysis band. It must be noted that this evaluation must be made via the actual LVDT motions (references) measured at the four wheel pans for the four axis road simulator application. In general, the excitation signals being sent to the input of each hydraulic actuator will be completely uncorrelated random but, due to structural interaction between the vehicle and the hydraulic actuators, the actual, measured input motions may be partially correlated. This is not a problem as long as the interaction is not severe enough to cause complete correlation at one or more frequencies. The use of singular value or eigenvalue decomposition of the \([G_{RR}]\) matrix, in the form of virtual references, is used during the measurement process to be certain that this requirement is met.
Chapter 3. Vehicle Comparisons via Transmissibility Function

3.1 Test Setup

Figure 4: UC-SDRL Four Axis Road Simulator

Testing was performed in the UC-SDRL High Bay Laboratory on the UC-SDRL (MTS 320) Four Axis Road Simulator. The laboratory is equipped with a service lift for installation of the vehicle on the four actuators (Model 248.03 Hydraulic Shakers). The service lift is mounted on an isolation mass (25’x14’x9” Concrete Inertia Mass) fitted with embedded steel plates for securing the actuators. The vehicle is secured to the actuator pans with heavy duty nylon straps.
The vehicle is typically instrumented with over 150 channels of acquisition which will be detailed below in Section 0.

With the vehicle positioned on the lift, drive files are generated. ‘Drive files’ are generated from supplied ‘Ride Files’ for the installed vehicle using an iterative process performed by MATLAB® based SimTest® software. Further discussion of this process can be found in Section 3.2. The vendor supplied a myriad of ‘Ride Files’ for use in testing, including ‘Belgian Block’, ‘Cobble Stone’, ‘Gravel’, ‘Harshness’, ‘NVH 1’, ‘NVH 2’, and ‘NVH 3’. The initial evaluation utilized these drive files until the correlation problem among the inputs (references) was noted.

3.1.1 Vehicles Tested

Testing was performed for four distinct vehicles. The tests are referred to in the order they were performed as Vehicle A, B, C, D, and E. Vehicle A was retested at a later date to incorporate best practices and was then referred to as Vehicle D. Vehicle E is considered Best in Class for this size vehicle based upon customer surveys, particularly with respect to NVH. Test dates are tabulated in Table 1 below.

<table>
<thead>
<tr>
<th>Test Dates</th>
<th>Vehicle</th>
<th>Type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/17/2006</td>
<td>Vehicle A</td>
<td>Sedan</td>
<td></td>
</tr>
<tr>
<td>10/04/2006 - 10/12/2006</td>
<td>Vehicle B</td>
<td>Coupe</td>
<td></td>
</tr>
<tr>
<td>10/26/2006 - 10/30/2006</td>
<td>Vehicle C</td>
<td>Sedan</td>
<td></td>
</tr>
<tr>
<td>12/07/2006 - 1/11/2007</td>
<td>Vehicle D</td>
<td>Sedan</td>
<td>Repeat of Vehicle A</td>
</tr>
</tbody>
</table>

Table 1: Testing Dates
3.1.2 Test Equipment

The intent of testing was to compare dissimilar vehicles. To accomplish this, it was desirable to make similar measurements on each vehicle. This requires installing instrumentation in analogous locations from one vehicle to the next (ex. Seat rail on each vehicle, cross body beam on each vehicle, etc.). Due to variations in geometry this was, at times, challenging. To aid in the organization of sensor locations and later comparisons a numbering scheme was established that was continued for each subsequent vehicles (Table 2).

<table>
<thead>
<tr>
<th>Numbering Scheme</th>
<th>Installation Location</th>
<th>Sensor Type</th>
<th>Nominal Sensitivity</th>
<th>Manufacturer</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td>Integral to Hydraulic Shaker</td>
<td>LVDT</td>
<td>3.34 V/in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Series</td>
<td>Wheel Pans</td>
<td>Uniaxial Accelerometer</td>
<td>1 V/G</td>
<td>PCB</td>
<td>UT333M07</td>
</tr>
<tr>
<td>20 Series</td>
<td>Wheel Spindles</td>
<td>Uniaxial Accelerometer</td>
<td>1 V/G</td>
<td>PCB</td>
<td>UT333M07</td>
</tr>
<tr>
<td>100/200 Series</td>
<td>A-Pillar</td>
<td>Triaxial Accelerometers</td>
<td>1 V/G</td>
<td>PCB</td>
<td>XT356B18</td>
</tr>
<tr>
<td>300/400 Series</td>
<td>B-Pillar</td>
<td>Triaxial Accelerometers</td>
<td>1 V/G</td>
<td>PCB</td>
<td>XT356B18</td>
</tr>
<tr>
<td>500 Series</td>
<td>Bulkhead/Firewall</td>
<td>Triaxial Accelerometers</td>
<td>1 V/G</td>
<td>PCB</td>
<td>XT356B18</td>
</tr>
<tr>
<td>600 Series</td>
<td>Cross Body Beam</td>
<td>Triaxial Accelerometers</td>
<td>1 V/G</td>
<td>PCB</td>
<td>XT356B18</td>
</tr>
<tr>
<td>700 Series</td>
<td>Seat Rails</td>
<td>Triaxial Accelerometers</td>
<td>1 V/G</td>
<td>PCB</td>
<td>XT356B18</td>
</tr>
<tr>
<td>800 Series</td>
<td>Seated Dummies</td>
<td>Microphones</td>
<td>20 mV/Pa</td>
<td>Modal Shop</td>
<td>130A10/P10</td>
</tr>
<tr>
<td>900 Series</td>
<td>Instrumentation Panel</td>
<td>Triaxial Accelerometers</td>
<td>1 V/G</td>
<td>PCB</td>
<td>XT356B18</td>
</tr>
</tbody>
</table>

Table 2: Instrumentation Details

Figure 5: Input Numbering and Direction Definition
Inputs were labeled as seen above in Figure 5. This notation was repeated wherever possible. For instance, the 100 series accelerometers were mounted on the driver’s side A-pillar while the 200 series accelerometers were mounted on the passenger side A-pillar. This notation was used on more minute instrumentation details as well. Seat rail accelerometers were labeled 711-714 on the driver’s side and 721-724 on the passenger side. In the case of sensor 713, the ‘7’ would indicate general placement (seat rail), the ‘1’ would indicate driver’s seat, and the ‘3’ would indicate the driver’s side aft corner of the seat rail.

Directions were defined such that the direction of travel would be the positive X direction, the positive Y direction is laterally from passenger to driver side, and the excitation is in the positive Z direction (upwards).

Instrumentation included microphones (Modal Shop Model 130A10/P10) and two different types of accelerometers (PCB Model Numbers XT356B18 and UT333M07). Typical sensors are shown in Figure 6 below.

Figure 6: Typical Sensors
Additional equipment is required for cable management, signal conditioning, and acquisition. To aid in cable management numerous ‘break out’ (PCB) boxes are utilized at various points around the vehicle. Signal conditioning is performed by PCB 441A101 power supplies and data acquisition is performed by a VXI System (HP E8400 A with Agilent/VTI Instruments 143x hardware). The acquisition mainframe with attached cabling for one of the test configurations can be seen below in Figure 7. All computation of transmissibility and related digital signal processing was accomplished with a custom MATLAB® script, included in Appendix G that utilized the sensor calibration information in an associated Excel documentation file. The Excel files for each of the Vehicles are included in Appendices A through E.

Figure 7: Data Acquisition Mainframe
3.2 Discussion of Road Simulator Input Characteristics

Traditional use of four axis road simulators in automotive testing involves using simulated road inputs for use in durability testing. These are generated by measuring response at a number of locations on the vehicle as it travels over a given terrain. The measured responses (referred to as the “ride files”) are then utilized in an iterative process, involving an inverse calculation, to estimate a set of input files for all axes of the road simulator that will be used to replicate the response as measured on the vehicle for the type of road input of interest (referred to as the “drive file”). This numerical procedure estimates a drive file based upon the characteristics and limitations of the specific road simulator being utilized. This numerical procedure, however, does not constrain the resulting drive files (inputs to the individual hydraulic actuators) to be uncorrelated and, experience with the UC-SDRL Four Axis Simulator indicates that, these types of inputs are, at times, significantly correlated. This will be examined further in Section 0.

While specific and measured vehicle responses, to a specific type of road surface, are commonly used as the basis for determining the displacement inputs to each axis of the road simulator when the system is used for durability or NVH studies, this will not be acceptable for the MIMO transmissibility case. Instead, uncorrelated random inputs are used to drive each of the four axes rather than using a drive file. Conventional drive file based data was taken for each vehicle as a requirement from the research partner but, in the end, this data was of no use for the transmissibility study. RMS levels of response at specified output response locations can be used to achieve response levels similar to those found in the ride files, if necessary.
3.3 Test Execution

The test execution was controlled by using MTS FlexTest software which allowed for the use of drive files and various general function generator type inputs (sine, random, etc.). The research partner supplied a myriad of ride files for each vehicle (used to generate drive files) for use in testing, including ‘Belgian Block’, ‘Cobble Stone’, ‘Gravel’, ‘Harshness’, ‘NVH 1’, ‘NVH 2’, and ‘NVH 3’. Drive files are generated from the ride files for each vehicle using a commercial, MATLAB® based program called SimTest®. Additionally, for the transmissibility study discussed in this thesis, each vehicle was tested with four random inputs generated by the MTS FlexTest software at three different magnitudes of input (referred to as 50%, 75%, and 100%). In this situation, the MTS FlexTest software, together with the MTS four axis road simulator hardware, was essentially a large, four axes, hydraulic shaker system with independently controlled inputs for each of the four axes.

Vehicle D was subjected to additional random excitation testing to determine the effects of various strapping conditions since data from the initial set of straps and data from the final set of straps was available. Note that each vehicle was delivered for testing over a two to three week time period and then returned to the research partner. Further testing of previous vehicles (B and C) with the new retention straps was not possible.
3.4 Strapping Effects

The research partner supplying the various vehicles for test typically tests in an unstrapped condition on shakers recessed into the floor in their facility. The UC-SDRL Four Axis Road Simulator tests vehicles in an elevated configuration since the hydraulic actuators are mounted on air suspension systems in the High Bay Laboratory. As such, strapping of the tire to the wheel pan is required for safety of the operator and vehicle under test. The addition of strapping will change the stiffness of the interaction of the wheel and the wheel pan. To assess this effect, an analytical model of the Four Axis Road Simulator, with a representative lumped mass vehicle model mounted on the Road Simulator, was developed. Note that this was discussed with the research partner prior to any testing and, since relatively low frequency comparisons were of greatest interest, was not deemed as a problem.

![Figure 8: Comparison of Straps Old (Left) vs. New (Right)](image)

However, during the course of testing, the original straps failed due to wear and required replacement. Replacement straps were of a different type and tightening mechanism. See Figure 8 for comparison of new straps to old. This loading (stiffness constraint) was not likely consistent with earlier testing. The model became useful in assessing this variation and defining the frequency limits where the strapping stiffness had little effect.
3.5 Four Axis Road Simulator Analytical Model

A simplified analytical model of the UC-SDRL Four Axis Road Simulator, with a lumped mass model of an automotive vehicle in position on the simulator, was developed in MATLAB®. The model is a 20 degree of freedom, lumped mass model as shown in Figure 9. The lumped mass parameters were chosen based upon the physical masses of the hydraulic actuator components and the physical mass and lumped mass distribution of a representative 3000 pound automotive vehicle.

Lumped stiffness and damping parameters were chosen to give known modal characteristics (frequencies and damping) of the various components. The first compression mode of the shakers is at 75 Hz. This information combined with the mass of the shaker was used to estimate the stiffness using the equation for undamped natural frequency.

\[ \omega = \sqrt{\frac{k}{m}} \]  

(27.)

This was not an exacting process but an attempt was made to get reasonable agreement between the model and measured transmissibilities in terms of magnitude and frequency characteristics and trends. The script that is utilized for implementation of this model is included in Appendix F.
Figure 9: Schematic of Vehicle Model

The various portions of the test setup are modeled as follows:

- $M_1 =$ Mass of a shaker post
- $M_2 =$ Un-sprung weight at each corner
- $M_3 =$ Mass of front/rear vehicle
- $M_4 =$ Mass of left/right vehicle
- $M_0 =$ Various vehicle masses

Note that all similar masses were set equal for simplicity. There is no such requirement in the model code found in Appendix F.
Model results will be presented in section 0 for various parts of the model including the wheel spindle, driver’s side vehicle structure, and forward vehicle structure. In general, transmissibility calculated from the FRFs of the model was compared to measured transmissibility in order to evaluate general agreement. Then the strapping stiffness was varied in the model to determine the affected frequency range. The conclusion was that the transmissibility characteristics were relatively unchanged below 25 Hz and, therefore, the transmissibility data with different strapping could be compared through 25 Hz. This also gave a reasonable frequency limit that was used for all final comparisons when looking for positive and negative trends between different vehicles.
3.5.1 Nominal Model Results

Figure 10: Driving Point Measurement Location

In the test configuration, an accelerometer was installed onto each wheel pan in order to estimate driving point transmissibility measurements (see Figure 10). Figure 11 shows a comparison of the driving point transmissibility measurement (right) to the driving point transmissibility simulation from the nominal model condition (left).

Figure 11: Comparison of Model (left) to Driving Point Measurement (right)
Additional comparisons of the model transmissibilities to analogous test data can be seen in Figure 12 and Figure 13 above. All magnitude units are g / inch and the trend characteristics between model and test are in good agreement.
3.5.2 Modeling Variable Strap Stiffness

As mentioned previously, in the course of testing, the vehicle retention straps broke. Exact duplicates could not be sourced, so another type of strap was substituted. The replacement straps had a different tightening mechanism and did not likely produce tightness consistent with the original straps. To assess the difference in strap tightness, the stiffness of the post-tire contact ($K_2$) was varied.

![Wheel/Wheelpan Transmissibility](image)

Figure 14: Effect of Strap Stiffness

From Figure 14, several conclusions were drawn. First, there is almost no effect of the strapping stiffness below 15 Hz, in either magnitude or phase. Second, when comparing transmissibilities, magnitude effects are of primary interest. Significantly different transmissibility magnitudes mean that the structures being compared will be much stiffer (with
less transmissibility) or less stiff (with greater transmissibility). Since measured transmissibilities exist for Vehicle D with both the original retention straps and the new retention straps, the retention strap tension was adjusted to get the best match possible for further testing. If only magnitudes are of interest, then the usable frequency range can be extended to 20 or even 25 Hz.

3.6 Transmissibility Results

Transmissibility data was compared from 0-30 Hz across all vehicles. Several samples of transmissibility data are provided below in Section 4.4.2. For a more comprehensive comparison of transmissibility for various vehicles, input levels and grouping, etc, please see the companion thesis [1].
3.6.1 Drive File Excitation

As discussed above, transmissibility calculations have a requirement that the inputs be uncorrelated. Upon examination of the virtual references for the various drive file cases, there were numerous examples where the four inputs were significantly correlated. The example in Figure 15 (left) shows a Belgian block drive file case where all four shakers are active, but there are only three independent excitations within the four excitation drive signals. This is compared to a random excitation case (right) in which all four inputs are uncorrelated.

Figure 15: Comparison of Correlated (Left) and Uncorrelated (Right) Inputs

While some drive cases yielded acceptable inputs over the frequency range of interest, several drive files yielded only two or three (as in the above example) independent inputs instead of the required four. For this reason, while input-output data was taken for each vehicle for all drive file cases, transmissibilities were not estimated from this data and this data was not used for further analysis.
3.6.2 Random Excitation

It is often desirable to compare data from different test levels, different tests conducted at different times or tests conducted to evaluate changes in the test object.

The following examples show comparisons of transmissibility functions with respect to different reference input levels.

![Figure 16: Wheel Spindle (Left) and Firewall (Right) Transmissibilities](image)

![Figure 17: Driver's Seat Rail (Left) and Passenger A-Pillar (Right) Transmissibility](image)

As Figure 16 and Figure 17 show, the measurements are fairly linear with respect to input level.
Another potential use for transmissibilities is comparisons of similar structures. Figure 18 and Figure 19 below show a comparison of transmissibilities among the various vehicles tested.

Figure 18: Wheel Spindle (Left) and Firewall (Right) Transmissibilities

Figure 19: Driver's Seat Rail (Left) and Passenger A-Pillar (Right) Transmissibility

Figure 20 and Figure 21 below show a comparison of transmissibilities for various strapping conditions on Vehicle D.
The above plots confirm the strapping stiffness has little to no effect on transmissibility magnitude below 15 Hz and very little effect on phase. Note that this is consistent with the model results in Section 3.5.2.
Chapter 4. Principal Component Analysis in Structural Dynamics

Much of the material of this chapter was originally published as a paper for the International Modal Analysis Conference [7]. The version originally published inadvertently included some acoustic measurements in the principal component analysis (PCA) calculations, which skewed the results. The data shown below has had the acoustic data removed. Some of the other PCA examples from this paper were reprocessed in the following sections of the thesis using transmissibility data from the testing of Vehicles B, C, D and E to be more relevant to the automotive testing situation.

4.1 Introduction

The concept of identifying the various underlying linear contributors in a set of data is needed in many fields of science and engineering. The techniques have been independently developed and/or discovered by many authors in many completely different application areas. Many times the procedure has acquired a different name depending upon the individual or specific application focus. This has resulted in a confusing set of designations for fundamentally similar techniques: Principal Component Analysis (PCA), Independent Component Analysis (ICA), Complex Mode Indicator Function (CMIF), Principal Response Functions, Principal Gains, and others. Without detracting from the insight and ingenuity of each of the original developers, each of these techniques relies upon the property of the singular value decomposition (SVD) to represent a set of functions as a product of weighting factors and independent linear contributions. Today, this is known more widely as the SVD approach to principal component analysis (PCA).
4.2 Nomenclature

- \( N_r = \) Number of inputs (references)
- \( N_o = \) Number of outputs.
- \( N_f = \) Number of frequencies.
- \( N_S = \) Short matrix dimension.
- \( N_L = \) Long matrix dimension.
- \( \omega = \) Frequency (rad/sec).
- \( \lambda_r = \) Complex modal frequency
- \( [B] = \) Generic data matrix.
- \( [H(\omega)] = \) Frequency response function matrix \((N_o \times N_i)\).
- \( [T(\omega)] = \) Transmissibility function matrix \((N_o \times N_r)\).
- \( [G_{RR}(\omega)] = \) Force cross power spectra matrix \((N_r \times N_r)\).
- \( [U] = \) Left singular vector matrix.
- \( [S] = \) Principal value matrix (diagonal).
- \( [\Sigma] = \) Singular value matrix (diagonal).
- \( [\Lambda] = \) Eigenvalue matrix (diagonal).
- \( [V] = \) Right singular vector, or eigenvector, matrix.
4.3 Background

Principal component analysis (PCA) is the general description for a number of multivariate data analysis methods that typically provide a linear transformation from a set of physical variables to a new set of virtual variables. The linear transformation is in the form of a set of orthonormal vectors (principal vectors) and associated scaling for the orthonormal vectors (principal values). These scaling terms are often thought of as the weight or importance of the associated orthonormal vectors since the orthonormal vectors have no overall scaling (unity length) but are orthogonal to one another (have no projection or relationship to one another).

While there are many approaches to computing the principal components, most modern implementations utilize eigenvalue decomposition (ED) methods for the square matrix case and singular value decomposition (SVD) for the rectangular matrix case.

Historically, the primary governing equation for the decomposition is as follows:

\[
[B]_{N_o \times N_r} = [U]_{N_o \times N_r} [S]_{N_r \times N_r} [U]^T_{N_r \times N_r}
\]  \hspace{1cm} (28.)

In this relationship, the common form starts with a data matrix ([B]) that is frequently real-valued and square which is transformed by the orthonormal vectors ([U]) and the diagonal principal value matrix. The form of the SVD equation given in Equation (28) is referred to as the economical form of the SVD. Since the orthonormal vectors have no scaling (unity length), the principal values contain the physical scaling of the original data matrix ([B]). The scaling nature of the principal or singular values gives rise to the term principal gain that is occasionally found in structural dynamics.

With respect to structural dynamics, the PCA is frequently performed time by time, or frequency by frequency, across a data matrix that is square or rectangular at each time or
frequency. The common form of the PCA concept when developed via the singular value decomposition of a complex-valued data matrix becomes:

$$[B]_{N_0 \times N_r} = [U]_{N_0 \times N_r} [S]_{N_r \times N_r} [V]^H_{N_r \times N_r}$$

(29.)

In this version of the relationship, still the economical from of the SVD, the common form starts with a data matrix ([B]) that is frequently complex-valued and rectangular which is transformed by the orthonormal vectors ([U]) and ([V]) and the diagonal principal value matrix ([S]). If the data matrix ([B]) is complex valued, it is important to note that the phasing between the left principal vector ([U]) and the associated right principal vector ([V]) is generally not unique. If the principal vectors are used independently (left or right singular vectors) this arbitrary phase issue must be accounted for.

Plotting the principal values, largest to smallest across the time or frequency range, results in a 2-D scaling function that is often used to determine specific time dependent or frequency dependent features in the data without the need to look at individual measurements. This can be tremendously helpful when the number of terms in the data matrix (rows and columns) is large.

The PCA techniques were first developed in the early 1900s but did not come into common use in structural dynamics until the 1970s and 1980s with the advent of math packages like EISPACK® and LINPACK® and subsequent development of user friendly software like Mathematica® and MATLAB®. A number of textbooks are now available that discuss these methods but many of the available texts do not include complex valued, spectral analysis that is common to structural dynamics data [5][6] [10][11][12][13][14][15].

PCA methods have found common usage in many science and engineering areas. The most common applications involve multidimensional scaling, linear modeling, data quality
analysis and analysis of variance. These are the same applications that make the general PCA methods so attractive to structural dynamics. Since much of structural analysis is built upon linearity, super-position and linear expansion, the PCA methods have found wide and increasing use, particularly in the experimental data analysis areas of structural dynamics. Common uses are the evaluation of force independence in the multiple input, multiple output (MIMO) estimation of frequency response functions (FRFs), the evaluation of close and repeated modal frequencies in the MIMO FRF matrix using a method that is known as the complex mode indicator function (CMIF) and the development of virtual FRF functions known as principal response functions.

4.4 Common Applications

With respect to structural dynamics, at least three PCA based methods are relatively well known and frequently utilized. The principal force analysis associated with MIMO FRF estimation, the close or repeated mode analysis of the complex mode indicator function (CMIF) and the virtual FRF estimation related to principal response functions have all been used for ten or more years and are summarized in the following sections.
4.4.1 Principal (Virtual) References

The current approach used to evaluate correlated inputs for the MIMO transmissibility or FRF estimation problem involves utilizing principal component analysis to determine the number of contributing references (principal or virtual references) to the $[G_{RR}]$ matrix [16][17][18]. The $[G_{RR}]$ matrix is the cross power spectra matrix involving all the multiple, simultaneous reference inputs applied to the structure during the MIMO transmissibility or FRF estimation. In this approach, the matrix that must be evaluated is:

$$[G_{RR}] = \begin{bmatrix} G_{RR_{11}} & \cdots & G_{RR_{1N_r}} \\ \vdots & \ddots & \vdots \\ G_{RR_{N_r1}} & \cdots & G_{RR_{N_rN_r}} \end{bmatrix} \quad (30.)$$

This application of PCA involves an eigenvalue decomposition of the $[G_{RR}]$ matrix at each frequency of the measured power spectra of the inputs (references). Since the eigenvectors of such a decomposition are unitary, the eigenvalues should all be of approximately the same size if each of the inputs is contributing to the excitation of the structure equally. If one of the eigenvalues is much smaller at a particular frequency, one of the inputs is not present or one of the inputs is correlated with the other input(s) at that frequency.

$$[G_{RR}(\omega)] = [V(\omega)][\Lambda(\omega)][V(\omega)]^H \quad (31.)$$

$[\Lambda]$ in the above equation represents the eigenvalues of the $[G_{RR}]$ matrix. If any of the eigenvalues of the $[G_{RR}]$ matrix are zero or insignificant, then the $[G_{RR}]$ matrix is singular. Therefore, for a four input test, the $[G_{RR}]$ matrix is 4x4 at each frequency and should have four eigenvalues at each frequency. (The number of significant eigenvalues is the number of uncorrelated inputs).
Figure 22: Principal (Virtual) Reference Spectrum – Random Excitation

Figure 22 shows the principal reference plots for a four input random excitation case. These principal reference curves are no longer linked to a specific physical exciter location due to the linear transformation involved. These curves are sometimes referred to as virtual inputs. Note that the overall difference in the four curves is typically one or two orders of magnitudes and there will be some fluctuation in the curves in the frequency region where there are lightly damped modes due to the exciter-structure interaction.
Figure 23 shows a case where drive file excitation was used. The distinct change in amplitude of the fourth curve indicates that there are only three independent references contributing to the reference power spectra matrix.

4.4.2 Complex Mode Indicator Function

Another application of the SVD approach to PCA, applied to multiple reference FRF measurements and identified as the Complex Mode Indication Function (CMIF), was first developed for traditional MIMO FRF data in order to identify the proper number of modal frequencies, particularly when there are closely spaced or repeated modal frequencies [19][20][21][22]. The CMIF indicates the existence of real normal or complex modes and the relative magnitude of each mode. This application is where the idea of applying the PCA
technique to transmissibility measurements from the four axis road simulator originates. Since each transmissibility matrix will always contain four references, and the economical SVD will generate four curves, comparison between and among vehicles or test conditions can be easily made, although no direct relationship to modal contribution is expected.

The CMIF is defined as the economical (function of the short dimension) singular values, computed from the MIMO FRF matrix at each spectral line. The CMIF is the plot of these singular values, typically on a log magnitude scale, as a function of frequency. The peaks detected in the CMIF plot indicate a normalized response dominated by one or more significant contributions; therefore, the existence of modes, and the corresponding frequencies of these peaks give the damped natural frequencies for each mode. In this way, the CMIF is using the PCA approach to take advantage of the superposition principle commonly known as the expansion theorem. In the application of the CMIF to traditional modal parameter estimation algorithms, the number of modes detected in the CMIF determines the minimum number of degrees-of-freedom of the system equation for the algorithm. A number of additional degrees-of-freedom may be needed to take care of residual effects and noise contamination.

$$[H(\omega)] = [U(\omega)] [\Sigma(\omega)] [V(\omega)]^H$$  \hspace{1cm} (32.)

Most often, the number of input points (reference points), \(N_r\), is less than the number of response points, \(N_o\). In the above equation, if the number of effective modes at a given frequency is less than or equal to the smaller dimension of the FRF matrix, \(N_e \leq N_l\), the singular value decomposition leads to approximate mode shapes (left singular vectors) and approximate modal participation factors (right singular vectors). The singular value is then equivalent to the scaling factor \(Q_r\) divided by the difference between the discrete frequency and the modal frequency \(j\omega - \lambda_r\). For a given mode, since the scaling factor is a constant, the closer the modal frequency is to
the discrete frequency, the larger the singular value will be. Therefore, the damped natural frequency is the frequency at which the maximum magnitude of the singular value occurs. If different modes are compared, the stronger the modal contribution (larger residue value), the larger the singular value will be. The peak in the CMIF indicates the location on the frequency axis that is nearest to the pole. The frequency is the estimated damped natural frequency, to within the accuracy of the frequency resolution.

Figure 24: Complex Mode Indicator Function (CMIF)

Since the mode shapes that contribute to each peak do not change much around each peak, several adjacent spectral lines from the FRF matrix can be used simultaneously for a better estimation of mode shapes. By including several spectral lines of data in the singular value decomposition calculation, the effect of the leakage error can be minimized. If only the quadrature (imaginary) part of the FRF matrix is used in CMIF, the singular values will be much more distinct.
4.4.3 Principal Response Functions

Similar in concept to the CMIF is the development of the Principal Response Functions (PRF) [23][24][25]. In this case, however, instead of performing the decomposition of the FRF data matrix frequency by frequency, the entire data matrix is arranged in two dimensions such that each column contains a single FRF and the singular value decomposition is then performed on this new data matrix.

\[ [A]_{(N_x \times N_y) \times N_f} = [\{H_{11}(\omega)\} \cdots \{H_{pq}(\omega)\} \cdots \{H_{N_x N_y}(\omega)\}] = [U][\Sigma][V]^H \]  

(33.)

It was then recognized that the left singular vectors \([U]\) are a function of frequency and contain the primary spectral characteristics and the singular values \([\Sigma]\) the relative contribution of those vectors to the global data matrix. By selecting only the 'r' most significant singular values and associated left singular vectors, the principal response functions are then defined as:

\[ [PRF] = [\tilde{H}] = [U_r][\Sigma_r] = [A][V_r] \]  

(34.)

The principal response functions reveal the nature of the noise and noise floor contained in the data and, contrary to normal intuition, demonstrates that more data is not always better. Once the real information in the data matrix is identified, the addition of more measurements can only contribute to the noise and hence effectively raises the noise floor and makes parameter identification more difficult.

In the following example, the transmissibility matrix \([T]\) is used in place of the FRF matrix \([H]\). The following two plots in Figure 25 reveal for vehicle B that, although there are 624 individual transmissibility measurements (154x4), only about 25 PRFs are necessary to explain the spectral information for the top four orders of magnitude of transmissibility. The left figure is the plot of the top 25 PRFs; the right figure is the top 300 PRFs. It becomes clear by
comparison that the additional PRFs, beyond 25 PRFs or so, primarily contribute noise and establish the measurement noise floor.

Figure 25: Vehicle B, First 25 (Left) and First 300 (Right) Principal Response Functions

4.5 Structural Dynamic Comparisons of Automotive Structures

The following is an example of applying the PCA technique to transmissibility data collected on the road simulator. The expectation is that this way of combining the data will be more useful than trying to look at single point or group transmissibility measurements point by point or group by group. The examples that follow are taken from a series of experimental tests performed on the four different, fully trimmed automotive structures (Vehicle B through Vehicle E). The data utilized for these examples was MIMO transmissibility functions ([T(ω)]) taken with the UC-SDRL Four Axis Road Simulator. The MIMO transmissibility data is in the form of acceleration referenced to displacement and the data matrix is 4 by 150 representing the 4 vertical displacements of the inputs of the Road Simulator and the 150 accelerometers located all over the vehicles. Note that in these cases, when different vehicles are compared, the response accelerometers were in approximately the same locations on the different vehicles. These tests
were conducted to compare and contrast vehicles that were in the same general class (in terms of size) but with clearly different characteristics, identified based upon owner feedback [1] [26].

4.5.1 Evaluation of Linearity/Time Variance/Repeatability

Comparing the principal components of a set of MIMO transmissibility data from different test levels, different tests conducted at different times or tests conducted to evaluate changes in the test object are good examples of the application of principal component analysis methods. The following examples use the SVD approach to PCA to evaluate changes in the transmissibility data matrix to different reference input levels. It is much easier to compare the principal values as a function of frequency for the entire data set rather than to compare specific measurement DOFs. In all of the following examples, all principal value curves are first compared, followed by a comparison of only the primary principal value curves and then only the secondary principal value curves.

In the following example, it is relatively easy to see that the response of Vehicle B, as measured by all of the transmissibilities for three different excitation levels is relatively independent of excitation level.
The next figures show the same information for Vehicle E for the same excitation evaluation.
Figure 28: Vehicle E, Three input levels, All Data, All Principal Components

Figure 29: Vehicle E, Three input levels, All Data, Primary and Secondary Principal Components

Figure 26 through Figure 29 show random excitation at three different magnitudes. The similarity of the three curves demonstrates that the system (test apparatus with installed vehicle) is linear with regard to input magnitude. Although it appears both vehicles are fairly linear, it
appears Vehicle E has a stronger linear relationship (since the principal value curves more closely match). Although this comparison has a limited sample size, it also suggests that the testing has good repeatability.

Note that this method allows the analyst to get a measure of system linearity without examining each of the 624 individual transmissibility measurements (154 x 4).

### 4.5.2 Evaluation of Test Parameters

During testing of a series of vehicles, the straps used to restrain the vehicle with respect to the four actuators of the UC-SDRL Four Axis Road Simulator were damaged and could not be used in further testing. The straps were replaced but the new straps were in a different configuration as well as being of different sizes. The SVD approach to PCA was utilized to evaluate both the before and after variation of the MIMO transmissibility data as well as to take a further look at the effects of using one or more straps to restrain the vehicle.
From Figure 30 and Figure 31, several conclusions were drawn. First, these plots confirm the model predictions that there is very little effect of the strapping stiffness below 15
Hz. Additionally, above 15 Hz, the primary principal value curves are not affected unless no straps or only one strap is installed. This was not anticipated.

4.5.3 Directional Scaling

Frequently, the dominant direction of response is not clear when working with fully trimmed vehicles and particularly vehicle subcomponents. The SVD approach to PCA can be used to compare the overall scaling of the response from X to Y to Z direction in the data. In the following examples (Figure 32 and Figure 33), the scaling of the Z direction can be seen to be at a higher level than the X and Y directions. The original paper[7] (on which this section is based) noted that the Z direction was much lower than the X and Y directions. This was due to the erroneous inclusion of high magnitude microphone data which was coded in the X and Y directions.
Figure 32: Vehicle B, Direction Comparisons, All Data, All Principal Components

Figure 33: Vehicle B, Direction Comparisons, All Data, Primary and Secondary Principal Components
Figure 34: Vehicle E, Direction Comparisons, All Data, All Principal Components

Figure 35: Vehicle E, Direction Comparisons, All Data, Primary and Secondary Principal Components
**Figure 36:** All Vehicles, X Direction Data, All Principal Components

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**Figure 37:** All Vehicles, X Direction Data, Primary and Secondary Principal Components

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Figure 38: All Vehicles, Y Direction Data, All Principal Components

Figure 39: All Vehicles, Y Direction Data, Primary and Secondary Principal Components
Figure 40: All Vehicles, Z Direction Data, All Principal Components

Figure 41: All Vehicles, Z Direction Data, Primary and Secondary Principal Components

Figure 36 through Figure 41 show a comparison of transmissibilities among the four vehicles tested for each direction (X, Y, and Z). Note the Vehicle E has significantly less transmissibility in the region from 10-20 Hz and higher transmissibility from 20-30 Hz when
compared to the field of vehicles tested. Due to strapping limitations, no conclusion can be drawn from the 20-30 Hz range. The fact that Vehicle E is the ‘best in class’ specimen suggests that lower transmissibility in the 10-20 Hz frequency range may be an important metric to track for future evaluations. It should be noted that these conclusions are only speculation and further testing with a more significant sample size will be needed to evaluate their validity. As an anecdotal piece of information, Vehicle E was the only vehicle tested that used screw fasteners to fasten interior trim panels and components. All other vehicles primarily used plastic interference fasteners, sometimes referred to as Christmas tree fasteners, for most of the attachment of interior trim and components.

4.5.4 Structure Comparisons

One of the primary reasons to compare different vehicles is to determine overall structure characteristics that affect some performance criteria (squeak and rattle performance, for example) in order to clearly see that one vehicle is different from other similar vehicles. In this case, the vehicles are clearly different and looking at individual measurements or modal properties may not easily give global or overall (similar or dissimilar) structure characteristics. It may already be apparent based upon the previous sections that comparing the principal value curves rather than individual or group transmissibilities is easier and allows trend information to more easily be identified.
When comparing the entire sets of data (as seen in Figure 42, Figure 44 and Figure 43), the trends regarding the lower transmissibility of Vehicle E from 10 – 20 Hz continue.
4.5.5 Structural Component/Sub-System Comparison

This case is similar to the previous case but is limited to a subset of the data in the region of the dashboard of each vehicle. Again, clear differences can be seen in the trend of the data with some vehicles.

Figure 44: All Vehicles, Dash SubSystem, All Principal Components
Figure 45: All Vehicles, Dash SubSystem, Primary and Secondary Principal Components

When comparing specific subsets of data (as seen in Figure 44 and Figure 45), the trends regarding the lower transmissibility of Vehicle E from 10 – 20 Hz continue.
Chapter 5. Conclusions and Future Work

5.1 Conclusions

The first half of this thesis has explored the background of transmissibility, the development of the MIMO transmissibility function, and the application of the MIMO transmissibility function on the UC-SDRL Four Axis Road Simulator. While this technique looks promising, it is not conclusive given the relatively small sample size. Only one of each vehicle type was available and little repeat testing was performed. Another challenge with this technique is that, due to accessibility issues, sensor location was not always consistent vehicle to vehicle. While this technique produced some useful results, it is tedious to make the comparisons and identify trends with direct use of MIMO transmissibility.

The second half of this thesis has explored the general background, development and application of Principal Component Analysis (PCA) to MIMO transmissibility measurements for the specific case of a four axis road simulator and structural comparison studies. It has been noted that techniques have been discovered and re-discovered over time as various analysis problems have been encountered. Regardless of their original development, these various ingenious decomposition techniques that reveal underlying linear contributors, all now share a common numerical foundation in the singular value decomposition. Nonetheless, the various intuitive physical interpretations of the MIMO transmissibility data matrix using PCA methods are highly valuable contributions to the structural dynamics community. With their broad applicability and ability to extract effective global trend information, the various PCA techniques provide the analyst with robust numerical tools for making informed structure comparison decisions.
5.2 Future Work

As mentioned previously, sensor locations were not always consistent from vehicle to vehicle due to variations in geometry and accessibility. Future work could look to PCA evaluation of group transmissibilities to help deal with these inconsistencies.

Principal components analysis of the various vehicles tested revealed a difference in transmissibility in the 10-20 Hz region between the ‘best in class’ vehicle and the rest of the field of specimens. Future testing with an expanded sample size could determine if this is a meaningful metric with regards to identifying vehicles that will have “good” NVH characteristics. This would include a more rigorous evaluation of the retention strap issue and possible testing on a four axis road simulator with recessed actuators that does not require the use of retention straps.
References


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Appendix F. System Model MATLAB® Code

% mts320_model.m
% This is a MATLAB script to solve a 20 DOF system model of
% the UC-SDRL Four Post Shaker with vehicle installed.
% Solution for FRF by Inverse of [B]

%**************************************************************************
% Authors: Randall Allemang - randy.allemang@uc.edu
% Matthew Allemang - allemam@email.uc.edu
% Date: 18-Apr-94
% Modified Date: 30-Jul-07
% Modified Date: 23-Nov-12
% Structural Dynamics Research Lab
% University of Cincinnati
% Cincinnati, Ohio 45221-0072
% TEL: 513-556-2725
% FAX: 513-556-3390
%**************************************************************************

clear;
clc;

% Setup a 20 dof system to simulate a vehicle on a four post shaker

Ndof = 20;
Ni = Ndof;
No = Ndof;

% Define the masses (in Slugs)

m1 = 1025 * .031081;    % Shaker Post Mass
m2 = 60 * .031081;      % Un-Sprung Mass at Each Corner
m3 = 600 * .031081;     % Mass of Front/Rear
m4 = (3000 * .031081 - 2 * m3) / 2;  % Mass of Left/Right
m0 = 100 * .031081;     % Various Other Masses

% Define the spring constants

k1 = (75 * 2 * pi)^2 * m1;  % 1st compression mode of the shakers k is lbf/ft
k2 = k1 * .15;
k3 = k1 * .5;
k5 = k1 * .2;
k0 = k1 * .3;

quesk = input('Enter Strap Stiffness Multiplier (1): ');

if isempty(quesk)
    quesk = 1;
end
k2 = k2 * quesk;

% Define the ratio between stiffness and damping matrix

damp_perc = .001;

% Assemble the Mass matrix

mass = zeros(Ndof,Ndof);

% Post masses
for ii=1:4;
    mass(ii,ii) = m1;
end

% Tire masses
for ii = 5:8;
    mass(ii,ii) = m2;
end

% Front/Rear masses
for ii = 9:10;
    mass(ii,ii) = m3;
end

% Left/Right masses
for ii = 11:12;
    mass(ii,ii) = m4;
end

% Other masses
for ii = 13:Ndof;
    mass(ii,ii) = m0;
end

% Assemble the stiffness matrix

stiff = zeros(Ndof,Ndof);

% 1st Level
for ii = 1:4
    stiff(ii,ii) = k1 + k2;
    stiff(ii,ii+4) = -k2;
    stiff(ii+4,ii) = -k2;
    stiff(ii+4,ii+4) = k2 + k3 * 2;
    stiff(ii+4,ii+8) = -k3;
    stiff(ii+8,ii+4) = -k3;
end

% 2nd Level
stiff(5,12) = -k3;
stiff(12,5) = -k3;

for ii = 6:8
stiff(ii,ii+3) = -k3;
stiff(ii+3,ii) = -k3;
end

% 3rd
kount = 3;
for ii = 9:12
    kount = kount + 1;
stiff(ii,ii) = k3 * 2 + k0 * 2;
stiff(ii,ii-4) = -k3;
stiff(ii-4,ii) = -k3;
    if ii ~= 12
        stiff(ii,ii-3) = -k3;
stiff(ii-3,ii) = -k3;
    else
        stiff(ii,5) = -k3;
        stiff(5,ii) = -k3;
    end
    stiff(ii, (ii + kount):(ii + kount + 1)) = -k0;
stiff((ii + kount):(ii + kount + 1),ii) = -k0;
end

% 4th Level
for ii = 13:20;
stiff(ii,ii) = k0;
end
stiff(13:14,9) = -k0;
stiff(9,13:14) = -k0;
stiff(15:16,10) = -k0;
stiff(10,15:16) = -k0;
stiff(17:18,11) = -k0;
stiff(11,17:18) = -k0;
stiff(19:20,12) = -k0;
stiff(12,19:20) = -k0;

% Assemble the damping matrix
damp = damp_perc * stiff;

% Assemble the matrix of zeros to build state space equations
null = zeros(Ndof,Ndof);

% Form 2N x 2N state space equation.
a = [null,mass;mass,damp];
b = [-mass,null;null,stiff];
[x,d] = eig(b,-a);

% Sort Modal Frequencies
orig_lambda = diag(d);
[Y,I] = sort(imag(orig_lambda));
lambda = orig_lambda(I);
xx = x(:,I);

% Normalize x matrix to real vectors if possible

NumPoles = length(lambda);
if((NumPoles < 2 * Ndof) | (NumPoles > 2 * Ndof)),
    disp('Error - Number of poles found invalid')
    break
end

for ii=1:2 * Ndof;
    xx(1:2 * Ndof,ii) = xx(1:2 * Ndof,ii) ./ xx(2 * Ndof,ii);
end

% Compute 'modal a' and 'modal b' matrix

Ma = diag(xx.'* a * xx);
Mb = (xx.'* b * xx);

% Extract modal vectors from state-space formulation

Psi(1:2 * Ndof / 2,:) = xx(2 * Ndof / 2 + 1:2 * Ndof,:);
clear a,clear b,clear x,clear d;

% Set up data type variables

NFmin = min(abs(imag(lambda ./ (2 * pi))));
NFmax = max(abs(imag(lambda) ./ (2 * pi)));
disp([' Range of damped natural frequencies: ',...'
    num2str(NFmin), ' to ',num2str(NFmax), ' (Hz)']);
Fmin = input('Enter minimum frequency (Hz): (0)');
if isempty(Fmin), Fmin = 0; end;
Fmax = input('Enter maximum frequency (Hz): (100)');
if isempty(Fmax), Fmax = 100; end;
BS = input('Enter number of frequencies: (512)');
if isempty(BS), BS = 512; end;
Type_xva = input('Enter type of TF data (X/R=0, V/R=1, A/R=2): (2)');
if isempty(Type_xva)
    Type_xva = 2;
end

frequency = linspace(Fmin,Fmax,BS);
Omin = Fmin*(2*pi);
Omax = Fmax*(2*pi);
Omega = linspace(Omin,Omax,BS);

% Add random noise to FRF data?

RandomPercent=input('Enter random noise factor: (0.001)');
if isempty(RandomPercent), RandomPercent=0.001; end;
for ii=1:BS;
    FRF(:,:,ii) = inv(-mass.*omega(ii).*omega(ii) + damp.*j.*omega(ii) + stiff)* ...
    (j*omega(ii))^Type_xva; %FRF in units requested
end;

for ii=1:Ni
    for jj=No
        frf = squeeze(FRF(ii,jj,:));
        irf = HP_ifft(frf,2);
        max_irf = max(abs(irf));
        irf = irf+RandomPercent*max_irf*rand(size(irf));

        frf = fft(irf);
        FRF(ii,jj,:) = frf(1:BS);
        %ii,jj
    end
end

% Set up PsiDOF array (default to x direction)

for ii=1:Ndof
    PsiDOF(ii,1) = ii;
    PsiDOF(ii,2) = 1;
end

% Plot requested FRF measurement to screen

scale = 360.0 / (2.0*pi);
chk = 0;
while(chk == 1)
    kk = input('Plot FRFs (Yes=1):  (0)');
    if isempty(kk),chk = 0; end;
    if isempty(kk),break; end;

    ii=input('Input DOF:  (1)');
    if isempty(ii),ii = 1; end;

    jj=input('Output DOF:  (1)');
    if isempty(jj),jj = 1; end;

    H = squeeze(FRF(jj,ii,:));
    figure;
    subplot(211),semilogy(frequency,abs(H))
xlabel('Frequency (Hz)'),ylabel('Magnitude'),grid
    title(['FRF:  H(',num2str(jj),',',num2str(ii),')'])
    subplot(212),plot(frequency,scale.*angle(H))
xlabel('Frequency (Hz)'),ylabel('Phase'),grid
end
freqax = linspace(Fmin,Fmax,BS - 1);
radax = freqax * 2 * pi;
for ii = 1:4
  for jj = 1:Ndof
    TRF(jj,ii,:) = squeeze(FRF(jj,ii,2:end)) ./ 
squeeze(FRF(ii,ii,2:end)); % Give A/A (ft/s^2 / ft/s^2)
    TRF(jj,ii,:) = squeeze(TRF(jj,ii,:)) .* radax' .* radax' .* -1; %
    Mult by j*omega squared which gives A/X (ft/s^2 / ft)
  end
end

TRF = TRF ./ 32.2; % 'A' Units from ft/s^2 to G's

TRF = TRF ./ 12; % 'X' Units from ft to in

% Mass Legend
% ===========
% m1-m4  Shaker Post Mass
% m5-m8  Un-Sprung Mass at Each Corner
% m9-m10 Mass of Front/Rear
% m11-m12 Mass of Left/Right
% m13-m20 Various Other Masses

figure(1)
subplot(211)
semilogy(freqax,abs(squeeze(TRF(1,1,:))))
hold all;
xlabel('Frequency (Hz)')
ylabel('Magnitude (G''s/inch)')
title(sprintf('Driving Point Transmissibility
    At The Wheel Pan'))
grid on
box on
ylim([10^-4 10^2])

subplot(212)
plot(freqax,unwrap(angle(squeeze(TRF(1,1,:)))).*180./pi)
hold all;
xlabel('Frequency (Hz)')
ylabel('Phase (degrees)')
ylim([-200 200])
set(gca,'YTick','-180:90:180')
grid on
box on

figure(2)
subplot(211)
semilogy(freqax,abs(squeeze(TRF(5,1,:))))
hold all;
xlabel('Frequency (Hz)')
ylabel('Magnitude (G''s/inch)')
title(sprintf('Wheel/Wheelpan Transmissibility'))
grid on
box on
ylim([10^-2 10^3])
subplot(212)
plot(freqax, angle(squeeze(TRF(5,1,:))).*180./pi)
hold all;
xlabel('Frequency (Hz)');
ylabel('Phase (degrees)');
ylim([-200 200]);
set(gca, 'YTick', -180:90:180);
grid on
box on

figure(3)
subplot(211)
semilogy(freqax, abs(squeeze(TRF(9,1,:))))
hold all;
xlabel('Frequency (Hz)');
ylabel('Magnitude (G''s/inch)');
title(sprintf('Fwd. Vehicle Structure/Wheelpan Transmissibility'))
grid on
box on
ylim([10^-4 10^2])

subplot(212)
plot(freqax, angle(squeeze(TRF(9,1,:))).*180./pi)
hold all;
xlabel('Frequency (Hz)');
ylabel('Phase (degrees)');
ylim([-200 200]);
set(gca, 'YTick', -180:90:180);
grid on
box on

figure(4)
subplot(211)
semilogy(freqax, abs(squeeze(TRF(11,1,:))))
hold all;
xlabel('Frequency (Hz)');
ylabel('Magnitude (G''s/inch)');
title(sprintf('Left Vehicle Structure/Wheelpan Transmissibility'))
grid on
box on
ylim([10^-4 10^2])

subplot(212)
plot(freqax, angle(squeeze(TRF(11,1,:))).*180./pi)
hold all;
xlabel('Frequency (Hz)');
ylabel('Phase (degrees)');
ylim([-200 200]);
set(gca, 'YTick', -180:90:180);
grid on
box on
Appendix G. Principal Reference and Response MATLAB® Code

%%
% Transmissibility Project Script - March 2013
%%
%**************************************************************************
% Authors: Allyn Phillips
%          Randall Allemang - randy.allemang@uc.edu
%          Thomas Steed - steedwt@email.uc.edu
%          Matthew Allemang - allemam@email.uc.edu
% Date:  17-Aug-06
% Modified: 03-Mar-13
% Structural Dynamics Research Lab
% University of Cincinnati
% Cincinnati, Ohio 45221-0072
% TEL: 513-556-2725
% FAX: 513-556-3390
%**************************************************************************

% Bring in *.SDF File
% Open file and identify number of channels and number time points
clear all;
close all;
[filename, pathname] = uigetfile({'*.sdf', 'SDF Files (*.sdf)'},'Select SDF Data File');
if(filename == 0), return, end;

clear options
% options.chans = 0:2;
options.offset = 0;
options.length = 1024;
options.chans = []; % null ... all channels

sdf = readDXopen([pathname filename],options);
sdf = readDXdata(sdf,options);
sdf = readDXclose(sdf,options);

nTimePts = double(sdf.dataHdr.num_of_points * sdf.scanBig.num_of_scan);

nChans = length(sdf.chanNum);

Tmin = 0;
SampleRate = 1 / (sdf.xdata(2) - sdf.xdata(1));
Tmax = nTimePts / SampleRate;
Fmin = 0;
Fmax = 0.8 * SampleRate / 2;

disp(['SDF File Information: ']);
disp([' ']);
disp(['Number of time points: ' num2str(nTimePts)]);
disp(['Number of channels: ' num2str(nChans)]);
disp(['Sample rate: ' num2str(SampleRate) ' Samples/Second']);

disp(['Starting Time: ' num2str(Tmin)]);
disp(['Ending Time: ' num2str(Tmax) ' Seconds']);
disp(['Minimum Frequency: ' num2str(Fmin) ' Hz']);
disp(['Maximum Frequency: ' num2str(Fmax) ' Hz']);
disp([' ']);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Load Channel Info
FileLoad = input('Load Excel Calibration/Info File (0=No, 1=Yes) (1) ');
if isempty(FileLoad), FileLoad = 1, end;
if (FileLoad==1),

%%%%%%

% Squeak & Rattle Sensor and Geometry Array Creation from Excel
% ----------------------------------
[filename1.pathname1] = uigetfile('*xls','Excel File (X-Modal UFF default format):');
if (filename1 == 0), return; end;
[aa,bb,cc] = xlsread([pathname1 filename1],'Sensor Information');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% While Loop To Break if Excel Channels Do Not Match Channels in SDF
% ----------------------------------
% condition=1;
% while(condition==1);
% excel_channels=length(aa);
% if excel_channels==nChans
% condition=0;
% else
% disp('Excel File Problem: Channel Mismatch!')
% break
% end
% end
else
% Set defaults if no Excel file loaded
aa = zeros(nChans,7); % Channel Number Defaults
bb = cell(nChans+2,7); % Point (DOF) Number Defaults
aa(:,1) = [1:nChans]; % Channel Number Defaults
aa(:,2) = [1:nChans]; % Point (DOF) Number Defaults
aa(:,3) = 1; % Point (DOF) Direction Defaults
aa(:,4) = 12; % Data Type Code
[bb{:,5}] = deal('-1'); % Model Number
aa(:,6) = -1; % Serial Number
aa(:,7) = 1.0; % Calibration (Volts/EU)
end

% Now check for valid entries
%*************************************************************

Chans = aa(:,1); % Channel Number Defaults
DOFs = aa(:,2); % Point (DOF) Number Defaults
DOFdirs = aa(:,3); % Point (DOF) Direction Defaults
DataType = aa(:,4); % Data Type Code
ModelNum = bb(:,5); % Model Number
SerialNum = aa(:,6); % Serial Number
Cal = aa(:,7); % Calibration (Volts/EU)

for ii=1:nChans
    if(isnan(Chans(ii))),disp('Excel File Problem: Channel NaN'),Chans(ii)=0;,
    end
    if(isnan(DOFs(ii))),disp('Excel File Problem: DOF NaN'),DOFs(ii)=0;,
    end
    if(isnan(DOFdirs(ii))),disp('Excel File Problem: DIR NaN'),DOFdirs(ii)=0;,
    end
    if(isnan(DataType(ii))),disp('Excel File Problem: Data Type NaN'),DataType(ii)=0;,
    end
    if(isempty(ModelNum(ii))),disp('Excel File Problem: Model Number NaN'),ModelNum(ii)='NONE';,
    end
    if(isnan(SerialNum(ii))),disp('Excel File Problem: Serial Number NaN'),SerialNum(ii)=-1;,
    end
    if(isnan(Cal(ii))),disp('Excel File Problem: Calibration NaN'),Cal(ii)=1.0;,
    end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Default Settings For Setup Menu
%-----------------------------

BS = 2048;
nshftperc = 50;
Ns = round(0.8 * (BS / 2));
nShft = BS * (nshftperc / 100);

ID_one = 'NONE';
ID_two = 'NONE';

% Default to first 4 channels as references

Nr = 4;
No = nChans;
No = 154; % Some error in the last few channels. Lets Just use 154
Win_code = 110;

% outputs = Chans;
outputs = [1:No]';
references = [1:4];
save Sponsor_defaults BS nshftperec Ns nShft ID_one ID_two No outputs Nr references Win_code
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Setup Menu
% ---------------
setup = 1;
while(setup == 1),
    op_code = menu('Enter Setup Option: ', ...  
                   'Load Default Settings', ...  
                   'Load Previous Settings', ...  
                   ['Time Domain Blocksize: ',sprintf('%5.0f',BS)], ...  
                   ['# of References: ',sprintf('%5.0f',Nr)], ...  
                   ['# of Outputs: ',sprintf('%5.0f',No)], ...  
                   ['Percent Overlap: ',sprintf('%5.0f',nshftperec)], ...  
                   ['Window Type: ',sprintf('%5.0f',Win_code)], ...  
                   ['Test Vehicle Model: ', ID_one], ...  
                   ['Test Description: ', ID_two], ...  
                   'Measure / Execute ! ', ...  
                   'EXIT');
    drawnow;

    if(op_code == 1),
        load Sponsor_defaults
    end

    if(op_code == 2),
        load Sponsor_previous
    end

    if(op_code == 3),
        BS = input('Enter Time Blocksize: (2048) ');  
        if isempty(BS), BS = 2048, end;
    end

    if(op_code==4),
        Nr = input('Enter Number of References: (16) ');  
        if isempty(Nr), Nr = 16, end;
        references=input('Enter Input Channel Number(s): ([1:4]) ');  
        if isempty(references), inputs = [1:4], end;
    end

    if(op_code == 5),
        No=input('Enter Number of Outputs: (16) ');  
        if isempty(No), No = 16, end;
        outputs = input('Enter Output Channel Number(s): ([1:16]) ');  
        if isempty(outputs), outputs = [1:16], end;
    end

end
if(op_code == 6), 
    nshftperc=input('Enter Percent Overlap: (50) ');
    if isempty(nshftperc), nshftperc = 50, end;
end

if(op_code == 7),
    Win_code = input('Enter DSP Window Type:(001 or 110) ');
    if isempty(Win_code), Win_code=001, end;
end

if(op_code == 8),
    ID_one = input('Enter Vehicle Model in Single Quotes: (Vehicle Z) ');
    if isempty(ID_one), ID_one = 'Vehicle Z', end;
end

if(op_code == 9),
    ID_two = input('Enter Test Description in Single Quotes: ');
    if isempty(ID_two), ID_two = 'Test Data Run', end;
end

if(op_code == 10),
    setup = 0;
end
if(op_code == 11),
    return
end
drawnow

save Sponsor_previous BS nshftperc Ns nShft ID_one ID_two No outputs Nr
references Win_code

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
% Windows
% -------
wnd = ones(1,BS);
if(Win_code==110)
    wnd = (cos(2*pi*(0:(BS-1))/BS) - wnd)/2; % Hanning
else
    wnd = ones(1,BS); % Rectangular
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

nEns = fix((nTimePts-BS) / nShft);

if nEns > 300
    nEns = 300; % Limit Averages For Large Data sets. (Don't have ALL day)
end

Grr = zeros(No,Nr,Ns);
% Do Principal References and PRFs

options.offset = 0;
options.length = BS;
options.chans = []; % null ... all channels

sdf = readDXopen([pathname filename], options);

Grr(No,Nr,Ns) = 0 + j*eps;

for ii = 1:nEns,
    options.offset = (ii-1)*nShft;
    sdf = readDXdata(sdf, options);

    % Multiply by window
    % Calibrate for sensor sensitivity (Cal in Volts/EU)
    % Calibrate for FFT blocksize
    for jj = 1:nChans,
        Sx(jj,:) = fft(sdf.ydata(jj,:) .* (wnd/(Cal(jj)*BS/2)));
    end

    % Sx = 1/(BS/2)*fft(sdf.ydata,[]),2);

    for jj = 1:Ns,
        Grr(1:No,1:Nr,jj) = Grr(1:No,1:Nr,jj) + Sx(outputs,jj) * Sx(references,jj)';
    end
end

sdf = readDXclose(sdf, options);

f = (0:(Ns-1)) / (sdf.xdata(end) + sdf.xdata(2) - 2*sdf.xdata(1));
Grr = Grr / nEns;

drawnow

figure
semilogy(f, abs(squeeze(Grr(1,1,:))));
semilogy(f, abs(squeeze(Grr(2,2,:))));
semilogy(f, abs(squeeze(Grr(3,3,:))));
semilogy(f, abs(squeeze(Grr(4,4,:))));
title(sprintf('Grr\n%s', strrep(filename, '_', ' \_' )));
xlabel('Frequency (Hz)');
ylabel('Magnitude (in^2)');
xlim([0 100]);

for ii = 1:Ns
    [u,s,v] = svd(squeeze(Grr(1:4,1:4,ii)));
    Vref(1:4,ii) = diag(s);
end

figure
semilogy(f, Vref(1,:));
hold all;
semilogy(f,Vref(2,:));
semilogy(f,Vref(3,:));
semilogy(f,Vref(4,:));
title(sprintf('Principal References
%s',strrep(filename,'_','\_')));
xlabel('Frequency (Hz)');
ylabel('Magnitude (in^2)');
xlim([0 100]);
grid on;
box on;

% Principal Response Functions
Goo = squeeze(Grr(5:154,1,:));
Goo = cat(1,Goo,squeeze(Grr(5:154,2,:)));
Goo = cat(1,Goo,squeeze(Grr(5:154,3,:)));
Goo = cat(1,Goo,squeeze(Grr(5:154,4,:)));

[u,s,v] = svd(Goo,'econ');
s2 = s;
s2(300:end,300:end) = 0;
PRF = u * s2;

figure
semilogy(f,abs(PRF(:,1:25)));
title(sprintf('Principal Response Functions
[25]\n%s',strrep(filename,'_','\_')));
xlabel('Frequency (Hz)');
ylabel('Magnitude (in^2)');
xlim([0 100]);
grid on;
box on;

figure
semilogy(f,abs(PRF(:,1:300)));
title(sprintf('Principal Response Functions
[300]\n%s',strrep(filename,'_','\_')));
xlabel('Frequency (Hz)');
ylabel('Magnitude (in^2)');
xlim([0 100]);
box on;