BASEBALL BAT MODEL IDENTIFICATION AND DETECTION OF SYSTEM CHANGES THROUGH IN SITU EXPERIMENTAL MODAL MODELS DEVELOPED ON THE FIELD

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ABSTRACT

Certification testing of baseball bat equipment is performed to ensure that a bat is in compliance with governing body (e.g. NCAA) regulations which are put in place to maintain the integrity of the game. At times, players have used bats that are illegally "doctored" to gain advantage in play. An in situ test is being investigated to use measured experimental modal data for comparison to existing analytical models. Model updating methodologies are employed to identify changes to the qualified bat configuration. In preliminary studies with wooden bats, changes in the system mass can be quantified and location of change identified. The techniques will be extended to aluminum bats where significant "doctoring" of the bat is more easily achieved by a variety of means than in wood bats, where corking in the most common illegal change in the bat.

INTRODUCTION

Currently, there are many regulations in place (NCAA, ASA, etc.) to maintain the integrity of play in baseball and softball. These regulations are intended to keep the batted-ball velocities limited to a standard that is intended to maintain the integrity of the game and to prevent unreasonable risk of injury to the players. While bats used in play must meet these certifications, there are times that bats (that have been certified) have been modified without knowledge or approval of the governing bodies. In fact, some instances have been identified where bats have been redesigned/modified and then painted to mimic a “certified bat”. In these instances, these bats have been found “in play” and have been used to gain an unfair advantage during a game. While there is concern over the use of illegal bats to gain a competitive advantage, there is a much higher concern as to the safety of players when illegal bats are introduced into the game.

To counter this problem, an in-situ testing approach is needed to identify if a “certified bat” has been modified. While the bat certification process is very time consuming and requires significant testing equipment, the in-situ testing technique must be easy to implement, require minimal equipment and be sensitive enough to detect small changes to the characteristics of the bat configuration. A portable testing system that enables the quick identification of dynamic characteristics of the bat configuration needs to be utilized in conjunction with an analysis system to reduce the data and compare to analytical models that represent the certified configuration.

This paper presents an approach to use measured dynamic data identifying the bat characteristics in conjunction with an existing analytical model that represents the certified bat configuration. The test data are collected at a very limited set of measurement locations and compared to a reduced model approximation of the bat. The measured data are then expanded to the full set of finite element DOF used to describe the bat. This expanded test model is then used in a direct analytical model updating procedure to determine if differences in the bat can be observed. The updated model is compared to the original model to identify (localize) the changes to the system. For the case of the bat, the approach is currently used to identify gross global changes in the system mass and stiffness as an identifier that the bat may have been altered.

This paper presents the analytical methods utilized in the development of this assessment system. Theory of model reduction, model expansion and analytical model updating are briefly summarized in support of the method. Several test cases on an actual wooden bat configuration are presented to show the suitability of the proposed technique.

THEORY AND PROPOSED METHOD

To develop appropriate models for the proposed methods to determine changes in the system characteristics, reduced order models along with model updating techniques are necessary. Each of these methods is only summarized here; details of the techniques are contained in the respective references. The following sections describe the theory related to the reduction and improvement of the baseball bat models.

Model Reduction:

Model reduction is necessary to develop very brief but accurate models for in-situ applications. The methods used have been previously presented in many applications. For this work, the reduction is specifically performed for the development of an accurate lower-order model for field use and verification of certified bats.

Several methods for reducing the analytical models have been utilized. Three common methods are Guyan [1], SEREP [2], and a Hybrid method [3]. In these methods, the relationship between the full set of degrees of freedom and a reduced set of degrees of freedom can be written as:

$$\{X_n\}=[T]\{X_a\} \tag{1}$$

All three methods require the formation of a transformation matrix that can project the full mass and stiffness matrices to a smaller size. The reduced matrices can be formulated as:

$$[M_a]=[T]^T[M_n][T] \tag{2}$$

$$[K_a]=[T]^T[K_n][T] \tag{3}$$

The Guyan reduction process [1] forms the transformation matrix as:

$$[T_s]=\begin{bmatrix}[I]\\ -[K_{dd}]^{-1}[K_{da}]\end{bmatrix} \tag{4}$$

The SEREP reduction process [2] produces reduced matrices for mass and stiffness that yield the exact frequencies and mode shapes as those obtained from the eigensolution of the full size matrix. The SEREP transformation is formed as:

$$[T_U]=[U_n][U_a]^g \tag{5}$$

The Hybrid method [3] utilizes the accuracy of the SEREP method and seeds the reduced matrices with reduced Guyan matrices to insure that the resultant reduced matrices are fully ranked for all cases. The Hybrid method transformation matrix is:

$$[T_H]=[T_S]+[[T_U]-[T_S]][[U_a][U_a]^T[T_U]^T[M_n][T_U]] \tag{6}$$

Analytical Model Improvement :

These analytical models are adjusted using experimental results through a direct model updating approach. Either the full space model or reduced model are used for this process; for the studies here expanded full space models were used.

From basic modal representation of the system, modal mass and stiffness are evaluated as:

$$[E]^T[M][E] = [\overline{M}] = [I] \tag{7}$$

$$[E]^T[K][E] = [\overline{K}] = [\Omega^2] \tag{8}$$

Using a generalized inverse of these equations, the mass and stiffness can be estimated as [4]:

$$[E^g]^T[I][E^g] = [M] \tag{9}$$

$$[E^g]^T[\Omega^2][E^g] = [K] \tag{10}$$

This approach works well for cases where the number of relevant modes is equal to the number of degrees of freedom. When the number of degrees of freedom is greater than the number of modes, seeding matrices can be used in conjunction with the experimental mode shapes as described in [5].

Improvement to these results can be performed as:

$$[M_I] = [M_S] + [V]^T[I - \overline{M}_S][V] \tag{11}$$

$$[K_I] = [K_S] + [V]^T[`\omega^2 + \bar{K}_S][V] - [[K_S][E][V]] - [[K_S][E][V]]^T \tag{12}$$

where:

$$[V] = [[E]^T[M][E]]^{-1}[E]^T[M] = [\overline{M}]^{-1}[E]^T[M] \tag{13}$$

PROPOSED APPROACH FOR REDUCING AND ADJUSTING MODELS

The proposed technique is overviewed in this section. A simple schematic is shown in Figure 1 to identify the process proposed.

- An analytical model of the bat is developed. This model is developed using simplistic finite element modeling techniques to describe the pertinent lower-order modes of the bat.
- An experimental modal test is performed at a very limited set of DOF.
- To compare the model to the measured test data, the analytical model must be reduced in size to that of the experimental measured set of DOF.
- The measured data from the bat must be expanded out over all the finite element DOF.
- The finite element model must be adjusted (updated) using a direct technique to determine changes in the system characteristics of mass and stiffness. The expanded, measured modal data will be used as targets for the adjustment process. The difference of the improved system and original system will provide an indication as to the change in the system characteristics.

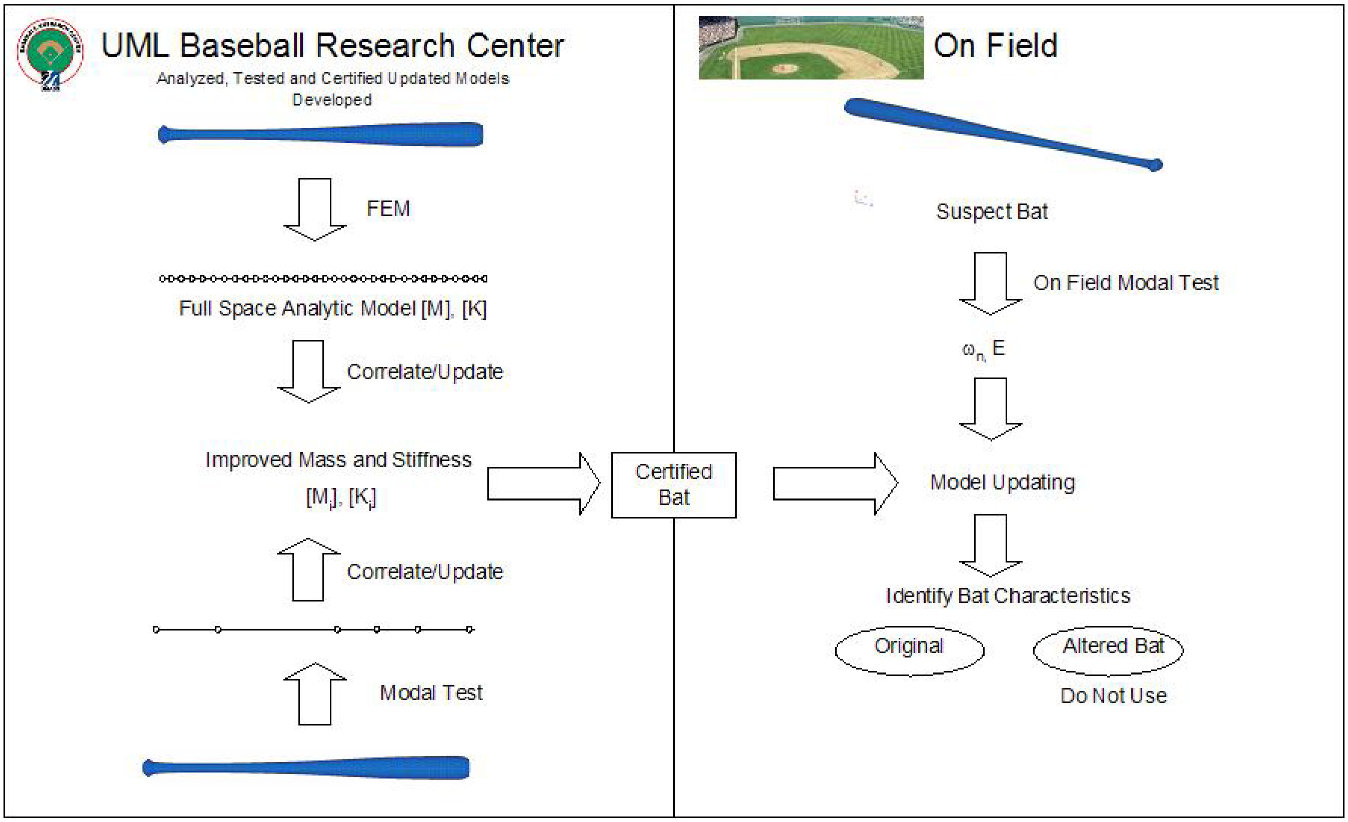

Figure 1 A simple schematic of the proposed approach for reducing and adjusting models

WOOD BAT MODELS DEVELOPED AND CASES STUDIED.

A finite element model of the bat was created. The model consisted of 32 planar beam elements with 33 nodes with 2 DOF per node. An eigensolution was performed to obtain the lower order modes of the system. An experimental modal test was performed for the original bat configuration. Data were collected using an FFT analyzer and data were reduced using ME'Scope [6]. Further manipulation of the data was performed using MATLAB [7]. The original finite element model was compared to experimental modal test data of the wood bat without any modifications. These measured data were used to update the finite element model to create an improved description of the baseline model.

A typical measured frequency response function is shown in Figure 2 along with the FEA and measured mode shapes. These data present the baseline for comparison to any modifications of the bat that may be investigated. Two cases were investigated as part of this study – both were mass modifications to the bat. One change was a typical weighted donut used for swinging practice and the other was a much smaller mass that was more than an order of magnitude smaller than the practice weight.

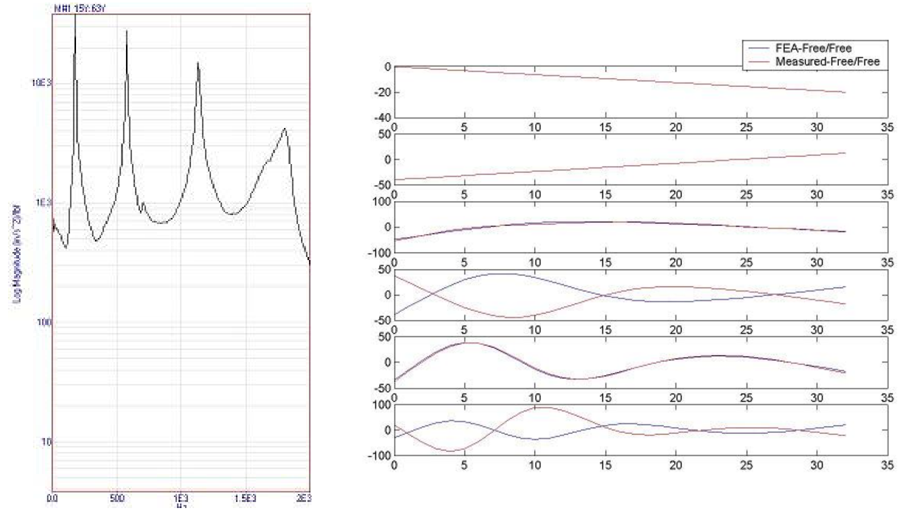

Figure 2 A typical FRF measurement and FEA and measured mode shapes for a wood bat without mass added

<u>Case 1 – 16 Oz Practice Weight</u>

A practice weight was added to the bat as shown in Figure 3. Experimental modal data were collected for the bat with the added weight. The data were compared to the reduced finite element model and expanded to the full set of finite element DOF. The direct analytical model improvement scheme was used to update the analytical model. The mass discrepancy was determined and a plot of the matrix difference is shown in Figure 4. There is very clear evidence that the updated mass shows substantial change to the system in the region of the actual applied weight. There is also some smearing beyond the specific region of the actual applied mass but it is very obvious that a change exists.

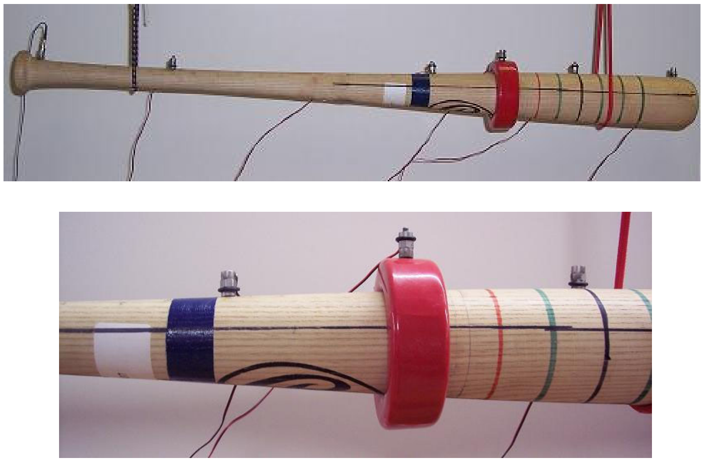

Figure 3 16-oz weight added to wood bat

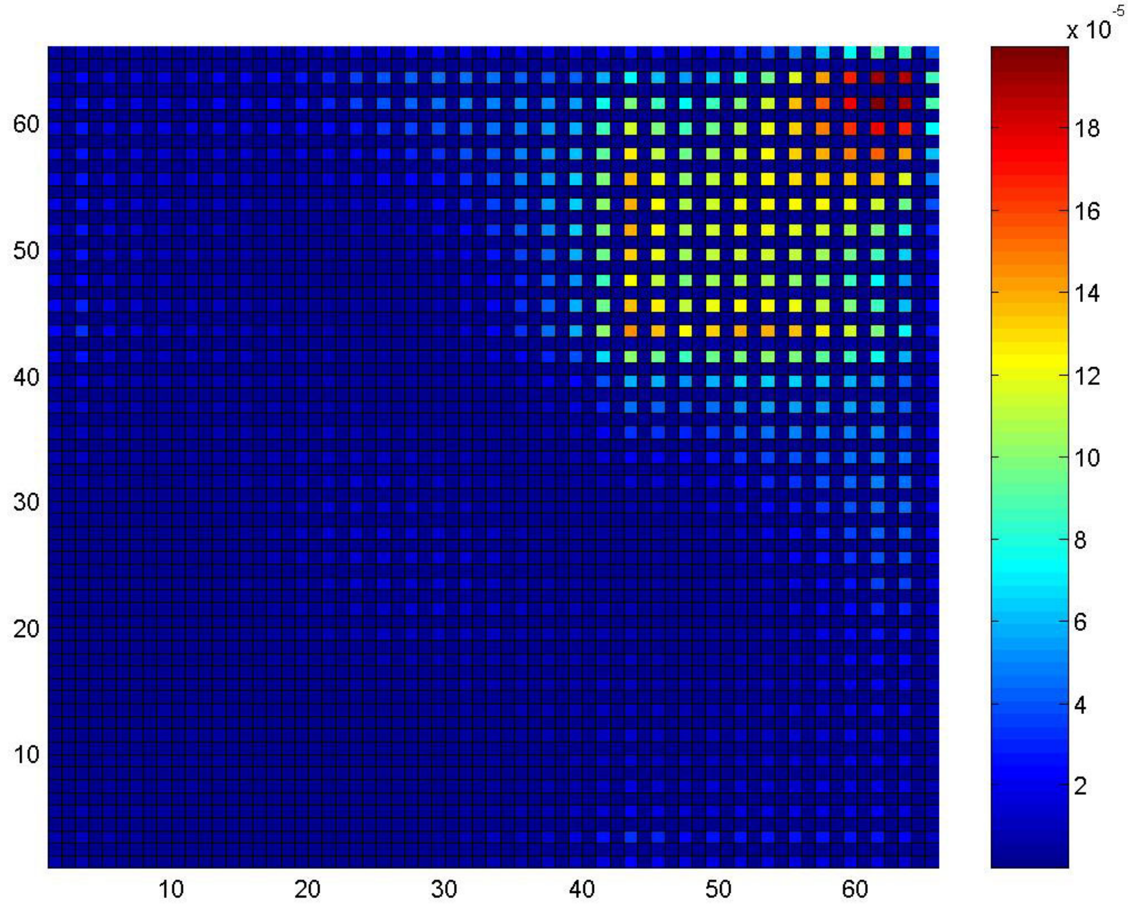

Figure 4 Difference of improved mass matrices with and without 16-oz weight added

Case 2 – 1 Oz Putty Weight

A weight was added to the bat using putty as shown in Figure 5. Another set of experimental modal data was collected for the bat with the added weight. Again, the data were compared to the reduced finite element model and expanded to the full set of finite element DOF. The direct analytical model improvement scheme was used to update the analytical model. The mass discrepancy was determined and a plot of the matrix difference is shown in Figure 6. As in the previous case, there is very strong evidence that the updated mass shows significant change to the system in the region of the applied weight. It is important to note that the scale of the matrices in Figures 4 and 6 have ratios that are approximately in the same order of magnitude as the actual masses used in the alteration process.

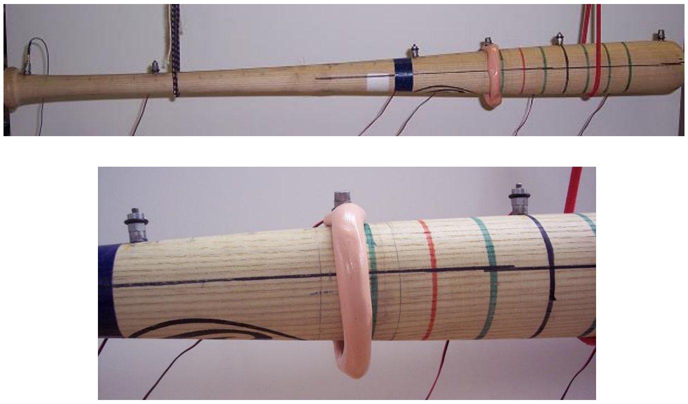

Figure 5 1-oz of putty added to wood bat

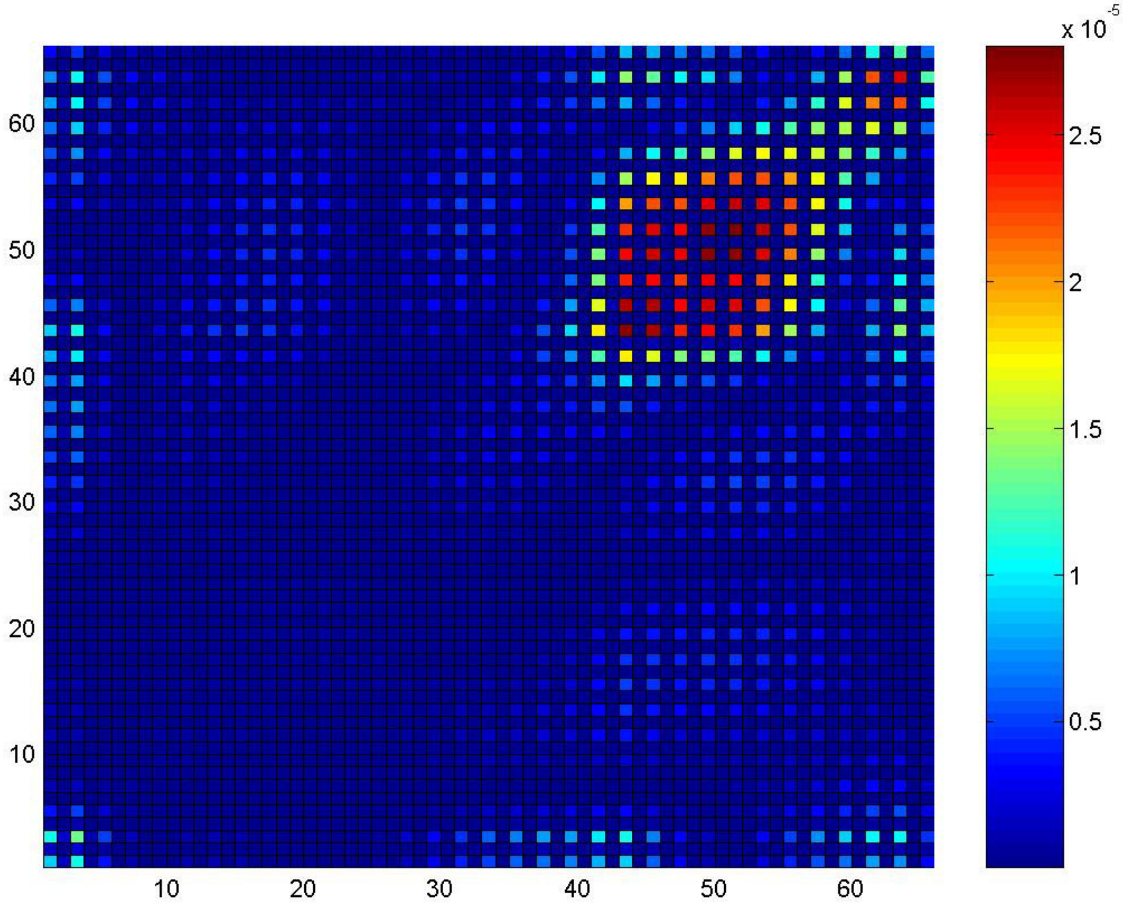

Figure 6 Difference of improved mass matrices with and without 1-oz of putty added

CONCLUSIONS

Certification of baseball and softball equipment is necessary to insure integrity of play and to prevent the exposure of the players to undue risk. At times, bats may be illegally altered to gain competitive advantage. An in-situ testing technique was proposed to identify alteration of baseball bats.

Using certified, updated analytical model representations of the bat developed in the laboratory along with experimental measured modal data collected on the playing field, an analytical model updating methodology was implemented to determine if a bat was subjected to alterations. From several different cases, the proposed approach is seen to have the ability to identify changes in the bat characteristics. This helps to identify if alterations to the equipment have been made.

The proposed technique shows promise as a detection tool. The methodology will be extended to cover a wider range of equipment including extension to aluminum and composite bat configurations.

NOTATION

Matrix

$[M]$	analytical mass matrix
$[K]$	analytical stiffness matrix
$[U]$	analytical modal matrix
$\left\lceil \overline{M} \right\rfloor$	diagonal modal mass matrix
$\left\lceil \overline{K} \right\rfloor$	diagonal modal stiffness matrix
$[T]$	transformation matrix
$[E]$	experimental modal vectors

Vector

$\{X\}$	displacement

Subscript

n	full set of finite element dof
a	tested set of experimental dof
d	deleted (omitted) set of dof
s	seed matrix
I	improved or updated matrix

Superscript

T	transpose
g	generalized inverse
-1	standard inverse

$$[V] = \left[[E]^T [M][E]\right]^{-1} [E]^T [M] = \left\lceil \overline{M} \right\rfloor^{-1} [E]^T [M]$$ generalized inverse

Acronyms

ADOF	Reduced degrees of freedom
AMI	Analytical Model Improvement method
SEREP	System Equivalent Reduction Expansion Process

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