Dynamic Design Of Drilling Machine Using Direct Method Based Updated FE Model

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ABSTRACT:

The aim of the present work is to develop an updated FE model of the drilling machine using analytical & experimental results, and to use this updated FE model to predict the effect of structural dynamic modifications on modal properties of the machine. Modal tests have been carried out on a drilling machine using instrumented impact hammer. Modal identification of the experimental FRFs has been carried out using ICATS software. The analytical FE results have been correlated with the experimental results using the above software. After correlation, the analytical FE model has been updated in the light of experimental data. This updated FE model has been used for computer level modifications and results are seen to be reasonably satisfactory.

INTRODUCTION:

Dynamic design aims at obtaining desired dynamic characteristics in products, equipments, systems and structures by specifying the right shape, size, configuration, material and manufacturing steps of various elements. Various tools of dynamic design are: Modal Testing, Modal Identification, Model Updating and Structural Dynamic Modification.

Modal testing is an experimental approach to obtain mathematical model of a structure. In a modal test the structure under test is excited, either by a impact hammer or by a modal exciter, and the response of the structure is recorded at the pre-defined experimental points, in the form of frequency response functions (FRFs), using a dual channel FFT analyzer. Modal Identification is the process in which we extract the modal model from the recorded FRFs. The modal model gives information about the natural frequencies, corresponding mode shapes and modal damping factor. Model updating techniques helps us to bring analytical finite element models closer to real systems. In model updating an initial theoretical FE model constructed for analyzing the dynamics of a structure is refined or updated using test data measured on actual structure such that the updated

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model describes the dynamic properties of the structure more correctly. In view of the availability of sophisticated instruments, experimental results obtained by modal testing are seen to be more accurate compared to those using FEM method in view of the uncertainties in boundary conditions and structural damping etc. in the later method. Structural dynamic modification (SDM) techniques can be defined as the methods by which dynamic behaviour of the structure is improved by predicting the modified behaviour brought about by adding modifications like those of lumped masses, rigid links, dampers etc. or by variation in the configuration parameters of the structure itself. The dynamic design using updated model is expected to be useful for SDM, to help us to predict, accurately and quickly, the effect of possible modifications like addition of masses, stiffeners and dampers etc. on the dynamic characteristics of the structure at computer level itself, thus saving time & cost.

MODAL TESTING & IDENTIFICATION:

The experimental setup is shown in Figure 1. Impact hammer is used to excite the drilling machine structure at various points as shown in Figure 2. Response is taken at a fixed point with the help of an accelerometer. Response in the form of FRFs is recorded in the FFT analyzer.

![Figure 1: Experimental setup](image1.png)  ![Figure 2: Hammer Excitation Locations](image2.png)

In the present case the drilling machine is excited at 30 locations and therefore, 30 FRFs are obtained. These FRFs are recorded in the form of inertance. The experimental FRFs, thus
obtained are transferred to computer for extraction of modal properties i.e. modal Identification in ICATS software. Modal identification or modal parameter extraction consists of curve fitting a theoretical expression for an individual FRF to the actual measured data obtained. The experimental FRFs are analysed by GRF-M method using modal analysis software ICATS to obtain modal parameters of the drilling machine.

FINITE ELEMENT FORMULATION OF DRILLING MACHINE:

The drilling machine structure is very complicated with different mountings and accessories. Therefore exact modeling and analysis of the actual structure is difficult and it takes more computational effort. However for analytical FE analysis, simplified model of drilling machines has been considered, which is shown in Figure 3. Beam elements have been used for the analysis, the joints and boundary conditions are considered to be rigid and influence of structural damping on modal model parameters, is ignored.

![Figure 3: Drilling Machine structure for FE analysis](image)

Relevant data for the drilling machine is as below:
Mass Density = 7800kg/m³, Young's Modulus = 200Gpa, Number of nodes = 30
Number of elements = 29, Number of nodes per element = 2, Degrees of freedom per node = 3

The Eigen values and Eigen vectors have been calculated from the assembled Mass [M] and Stiffness [K] matrices, using a program developed in MATLAB.
COMPARISON OF FEM AND EXPERIMENTAL RESULTS:

Table 1 shows that the experimental natural frequencies and analytical natural frequencies are close to each other. The difference between analytical FE model predictions of natural frequencies and experimental results is due to assumptions and approximations involved in the FE model.

Table 1: Comparison of analytical & experimental model natural frequencies.

<table>
<thead>
<tr>
<th>Mode Number</th>
<th>Analytical Model</th>
<th>Experimental Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>10.57 HZ</td>
<td>8.67 HZ</td>
</tr>
<tr>
<td>Mode 2</td>
<td>64.44 HZ</td>
<td>47.34 HZ</td>
</tr>
<tr>
<td>Mode 3</td>
<td>129.31 HZ</td>
<td>127.36 HZ</td>
</tr>
<tr>
<td>Mode 4</td>
<td>163.74 HZ</td>
<td>152.08 HZ</td>
</tr>
</tbody>
</table>

To compare mode shapes we plot the deformed shapes of each model, both experimental & analytical side-by-side. This is a graphical approach to model correlation. Mode shape corresponding to second mode is shown in figure 4, which shows a good level of correlation.

Figure 4: mode shape comparison
Several researchers have developed techniques for quantifying the comparison between measured and predicted mode shapes. As an alternative to the graphical approach, MAC (Allemang and Brown, [1982]) is a widely used technique to estimate the degree of correlation between mode shape vectors and this provides a measure of the least squares deviation or ‘scatter’ of the points from the straight-line correlation. MAC is a scalar quantity whose value is between 0 and 1. We can see in the bar chart shown in figure 5 that the MAC numbers of first & second modes are close to 1, so for these modes, analytical FE modes are well correlated with experimental modes. However for the third mode correlation is not so good. Fourth mode shows a poor correlation between the theoretical and experimental mode shapes. The reason for getting low level of correlation for higher modes may be the use of impact hammer for excitation.

**FINITE ELEMENT MODEL UPDATING USING DIRECT METHOD:**

Model updating corrects the numerical values of individual parameters in a analytical model using data obtained from an associated experimental model .The updated model is expected to correctly describe the dynamic characteristics of the structure. Two direct methods are applied to update the analytical FE model of the drilling machine structure. The advantage of direct method is that they are non-iterative method and reproduces the measured frequency exactly.
Baruch [1978] and a later modification to the method, known as Baruch and Bar-ltzhack [1978] considered the mass matrix of the analytical model to be exact. The measured eigenvectors are corrected by using the formula:

\[ \phi = \phi_m [\phi^T_m M_a \phi_m]^{1/2} \]

The stiffness matrices of the analytical FE model after updating i.e. updated stiffness matrix is given as:

\[ K_u = K_a - K_a \phi^T M_a + M_a \phi^T K_a + M_a \phi^T K_a \phi^T M_a + M_a \phi^T M_a \phi^T M_a \]

Berman and Nagy [1983] used a method similar to that of Baruch. They update mass and stiffness matrices while the mass matrix is updated to ensure the orthogonality of the exact FE model modes. The mass matrix is updated as:

\[ M_u = M_a + M_a \phi_m \overline{M_a}^{-1} (I - \overline{M}_a) \overline{M}_a^{-1} \phi^T M_a \]

\[ \overline{M}_a = \phi^T M_a \phi_m \]

The stiffness matrix is updated using following formulae

\[ K_u = K_a - K_a \phi_m \phi^T M_u + M_u \phi_m \phi^T K_a + M_u \phi_m \phi^T K_a \phi_m \phi^T M_a + M_u \phi_m \phi^T M_a \]

Results obtained from Baruch-Bar ltzhack and Berman-Nagy model updating method are tabulated in Table 2.

Table 2: Comparison of theoretical, experimental & updated frequencies

<table>
<thead>
<tr>
<th>Mode Number</th>
<th>Analytical Model (Reduced)</th>
<th>Experimental Model</th>
<th>Updated (Baruch and Bar-ltzhack)</th>
<th>Updated (Berman &amp; Negi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>10.2978Hz</td>
<td>8.6784Hz</td>
<td>8.6784Hz</td>
<td>8.6784Hz</td>
</tr>
<tr>
<td>Mode 2</td>
<td>65.1457Hz</td>
<td>47.3464Hz</td>
<td>47.3464Hz</td>
<td>47.3464Hz</td>
</tr>
<tr>
<td>Mode 3</td>
<td>128.7453Hz</td>
<td>127.366Hz</td>
<td>127.366Hz</td>
<td>127.366Hz</td>
</tr>
<tr>
<td>Mode 4</td>
<td>164.6547Hz</td>
<td>152.0845Hz</td>
<td>152.0845Hz</td>
<td>152.0845Hz</td>
</tr>
</tbody>
</table>

It is clear from the above table that the updated model reproduces the first four measured natural frequencies. After updating MAC values have been calculated again, which is shown in Figure 6 & 7. From the Figure 6 & 7, it can be observed that there is a good degree of mode shape correlation between analytical and experimental model.
STRUCTURAL DYNAMIC MODIFICATION USING UPDATED FE MODEL:

Structural Dynamic Modification techniques are methods by which dynamic characteristics of the structure can be improved by adding the modifications like those of mass, spring, damper etc. The mass modification has been considered for predicting dynamic characteristics using updated FE model.

MASS MODIFICATION ON DRILLING MACHINE:

A mass modification on drilling machine is introduced in the form of a lumped mass of 14.3 kg. at the top of the vertical pillar of the machine i.e. at node 20 as shown schematically in Figure 8. The modal test for the mass modified machine is carried out by Modak [2001]. The FRFs are analyzed in ICATS in order to obtain an experimental estimate of the altered dynamic characteristics in the drilling machine.

The effect of the same mass modification on the dynamic characteristics of the drilling machine has also been predicted by updated FE model. The Table 3 gives a comparison of the predictions based on the updated FE model with that of the measured modified characteristics.
Table 3: Comparison of measured & predicted frequencies

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Measured Frequency (Unmodified)</th>
<th>Measured Frequency (Modified)</th>
<th>SDM Predictions using Updated FE Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Baruch’s Method</td>
</tr>
<tr>
<td>1</td>
<td>8.67 HZ</td>
<td>8.37 HZ</td>
<td>8.34 HZ</td>
</tr>
<tr>
<td>2</td>
<td>47.34 HZ</td>
<td>46.05 HZ</td>
<td>47.15 HZ</td>
</tr>
</tbody>
</table>

It is seen from the Table 3 that the updated FE model predictions of the natural frequencies are quite close to the measured value of natural frequencies. This shows the capability of the updated FE model to accurately predict the effect of structural modifications on the dynamic properties of the structure.

SOME STUDIES ON MASS MODIFICATION USING UPDATED FE MODEL:

The mass modification can bring about significant changes in the natural frequencies of a structure. For predicting the effect of modifications using updated FE model, modification at location of node 25 on the drilling machine has been considered. The values of natural frequencies have been predicted using updated FE model.
Again a concentrated mass has been attached at node 25 as shown in Figure 9. Natural frequencies have been predicted with the help of updated FE model using FEM programme and Modify module in ICATS software. The results of the predictions are shown in Table 4.

Table 4: Predicted natural frequencies after mass modification

<table>
<thead>
<tr>
<th>Measured Natural Frequency (Hz)</th>
<th>Updated Natural Frequency (Hz)</th>
<th>SDM Predictions using Updated FE Model (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mass 20 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Baruch’s Method</td>
</tr>
<tr>
<td>8.67</td>
<td>8.67</td>
<td>8.34</td>
</tr>
<tr>
<td>47.34</td>
<td>47.34</td>
<td>42.24</td>
</tr>
<tr>
<td>127.36</td>
<td>127.36</td>
<td>119.24</td>
</tr>
<tr>
<td>152.08</td>
<td>152.08</td>
<td>149.00</td>
</tr>
</tbody>
</table>

We can see from the Table 4 that the results predicted by various methods are very close to each other. Also due to mass modification at node 25 there is a significant shift in 2\textsuperscript{nd} & 3\textsuperscript{rd} natural frequencies. Figure 9 &10 shows the regenerated FRF and shift in natural frequencies due to mass modification at node 25 & 30 respectively, using modify module in ICATS software.

Figure 9: Regenerated FRF due to Mass Modification at Node 25

Figure 10: Regenerated FRF due to Mass Modification at Node 30
Mass & stiffness modifications at some other nodes were also tried using updated models and the results were found to be reasonably satisfactory.

CONCLUSIONS:

Results obtained from experimental and analytical models clearly reveal that the analytical Finite Element models fail to predict dynamic behavior of the complex structure with an acceptable accuracy because of uncertainty in joints and boundary conditions. This gives rise to the need of correcting and updating FE models. An experimentation involving modal testing has been carried out on the drilling machine using impact hammer. Analytical FE model has been updated in the light of experimental data using direct methods. In order to improve the dynamic behavior of drilling machine, structural modification has been applied on the updated FE model of drilling machine and effects on the dynamic characteristics of the machine are predicted at computer level. It is observed that computer level SDM can be employed on complex structures like that of a drilling machine to save a lot of vibration design time.

REFERENCES: