Studies in dynamic design of drilling machine using updated finite element models

R.S. Bais a,*, A.K. Gupta b, B.C. Nakra c, T.K. Kundra c

a Bharat Heavy Electricals Limited, Hyderabad, India
b Instrument Research & Development Establishment, Dehradun, India
c Department of Mechanical Engineering, IIT Delhi, Delhi, India

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Abstract

The aim of the present work is to develop updated FE models of a drilling machine using analytical and experimental results. These updated FE models have been used to predict the effect of structural dynamic modifications on vibration characteristics of the drilling machine. Two studies have been carried out on the machine. In the first study, modal tests have been carried out on a drilling machine using instrumented impact hammer. Modal identification has been done using global method of modal identification. For analytical FE modeling of the machine, a computer program has been developed. The results obtained using FEM, have been correlated with the experimental ones using mode shape comparison and MAC values. Analytical FE model has been updated, with the help of a program, which has been developed using direct methods of model updating. In the second study, modal testing has been carried out using random noise generator and modal exciter. Global method has been used for modal identification. Analytical FE modeling has been done using I-DEAS software. Correlation of FE results with the experimental ones has been carried out using FEMtools software. Updating of the analytical FE model has also been done using the above software, based on an indirect technique viz. sensitivity based parameter estimation technique. The updated FE models, obtained from both the studies have been used for structural dynamic modifications (SDM), for the purpose of dynamic design and the results of SDM predictions are seen to be reasonably satisfactory.
1. Introduction

Dynamic design aims at obtaining desired dynamic characteristics in machines and structures, which may include shifting of natural frequencies, desired mode shapes and vibratory response. The ultimate objectives are to have a quieter and more comfortable environment, higher reliability and better quality of product. The conventional dynamic design is basically hit and trial method in which we try to achieve desired dynamic characteristics by making several prototypes. The disadvantage of this technique is that actual design cycle takes a lot of time and therefore it is not cost effective. However, model updating based dynamic design saves design cycle time as well as reduces the cost involved. Various tools used for updating based dynamic design are: experimental modal analysis (EMA) including modal testing and modal identification, model updating and structural dynamic modification.

Ewins [1] and Maia and Silva [2] have explained the basic concepts of modal testing, which is an experimental approach to obtain mathematical model of a structure. In a modal test, the structure under test is excited either by an impact hammer or by a modal exciter, and the response of the structure is recorded at several experimental points, in the form of frequency response functions (FRFs), using a dual channel FFT analyzer. The experimental modal model gives information about the natural frequencies, corresponding mode shapes and modal damping factor and is useful for model updating. The model updating techniques helps us to bring analytical finite element models closer to real systems. In model updating an initial analytical 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 model describes the dynamic properties of the structure more correctly. The inaccuracies in FEM, when applied to dynamic problems are due to uncertainties in boundary conditions and structural damping etc.

Friswell and Mottershead [3] have discussed the finite element model updating in structural dynamics. Baruch and Bar-Itzhack and Baruch [4,5] considered analytical mass matrix to be exact...
and developed a direct method for updating using test data. Berman and Nagy [6] developed a method of model updating, which uses measured modes and natural frequencies to improve analytical mass and stiffness matrices. Structural dynamic modification (SDM) techniques [7,8] are 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. Thus the dynamic design using updated model is expected to be helpful in order to predict accurately and quickly, the effect of possible modifications on the dynamic characteristics of the structure at computer level itself, thus saving time and cost.

Sestieri [7] has discussed SDM application to machine tools and engines. Kundra [8] gave the method of structural dynamic modification via models. Modak [9] has discussed SDM predictions using updated FE model for an F-structure. He used constrained nonlinear optimization method for updating of a machine tool using stiffness parameters at the boundary [10]. The present paper deals with the FE model updating using direct as well as indirect method, and to use this updated FE model for dynamic design based on SDM predictions of a machine tool viz. a drilling machine. Two different studies are reported using different techniques for analytical and experimental analysis and for updating. Various objectives with which the present research work has been carried out are

- To develop updated FE models of a complex structure like that of a drilling machine and to use these updated models to predict the effect of various modifications on modal properties of the machine.
- To see whether hammer excitation yields good results for fairly complex structures like drilling machine or not, and to compare these results with those obtained from modal exciter.
- To analyze the results of SDM predictions obtained using the updated models derived in the studies.

2. Modal testing and identification

In the two studies mentioned earlier, different techniques have been used, for modal testing and identification. In the first study, impact hammer is used to excite the drilling machine structure, at various points as shown in Figs. 1 and 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.

In the present study, the drilling machine is excited at 30 locations and therefore, 30 FRFs are obtained. These FRFs are obtained 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 analyzed by GRF-M method using modal analysis software ICATS [11] to obtain modal parameters of the drilling machine. In the second study, the machine tool structure has been excited at the base at point 28, referring to Fig. 2, using modal exciter and response has been measured at various points using piezoelectric accelerometers. The modal identification of the FRFs, thus measured has been carried out using global method GRF-M method in ICATS software.
Table 1 compares the experimental natural frequencies obtained from both the methods, which shows minor differences in the two modal frequencies and MAC values.

3. Finite element formulation of drilling machine

Several books have given the basic concepts of finite element analysis, some of them are: Zienkiewicz [12] and Bathe [13].

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. In study 1, the finite element modelling has been done using a program developed in MATLAB. Beam elements have been used for the analysis. The joints and boundary con-
Table 1
Comparison of analytical and experimental model natural frequencies

<table>
<thead>
<tr>
<th>Mode number</th>
<th>Study 1</th>
<th></th>
<th></th>
<th>Study 2</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analytical model</td>
<td>Experimental model</td>
<td>MAC values</td>
<td>Analytical model</td>
<td>Experimental model</td>
<td>MAC values</td>
</tr>
<tr>
<td>Mode 1</td>
<td>11.20 Hz</td>
<td>8.67 Hz</td>
<td>0.953</td>
<td>11.20 Hz</td>
<td>8.79 Hz</td>
<td>0.946</td>
</tr>
<tr>
<td>Mode 2</td>
<td>63.37 Hz</td>
<td>47.34 Hz</td>
<td>0.901</td>
<td>63.37 Hz</td>
<td>44.40 Hz</td>
<td>0.906</td>
</tr>
</tbody>
</table>

ditions are considered to be rigid and influence of structural damping on modal model parameters, is ignored. The relevant data used for the drilling machine is given below:

25 mm pillar type, height = 1.655m, mass density = 7800 kg/m³, Young's modulus = 200 Gpa, number of nodes = 30, number of elements = 29, number of nodes per element = 2, degrees of freedom per node = 3.

Fig. 3 shows the structure of the drilling machine with the node numbers given for study 1.

The eigenvalues and eigenvectors have been calculated from the assembled mass $M$ and stiffness $K$ matrices. The analytical FE model of the structure consists of 90 x 90-size mass and stiffness matrices (30 x 3, 30 nodes and 3 d.o.f. per node). But by experiment only 30 coordinates can be measured. Therefore FE model has been reduced using Guyan [14] reduction method with the help of a program developed in MATLAB.

In study 2, the finite element modelling has been done using I-DEAS software. The model has been made using beam mesh. Although the FE model has been simplified but the beam elements has rotational degree of freedom, which cannot be measured experimentally. Therefore the FE model needs to be reduced. The FE model has been reduced using model reduction utility in FEMtools software. Figs. 4 and 5 shows the mode shape animation for the first and second mode respectively, using I-DEAS software.
Fig. 4. Mode shape animation (first mode).

Fig. 5. Mode shape animation (second mode).
Table 1 compares the analytical FE natural frequencies obtained from both the methods, with some differences in the two cases.

4. Comparison of analytical FE and experimental results (model correlation)

The first stage of any reconciliation exercise is to determine how closely the experimental and analytical models correspond. If we are unable to obtain a satisfactory degree of correlation between the initial analytical FE model and the test data, then it is extremely unlikely that any form of model updating will succeed. Thus, a successful correlation is crucial for the success of model updating. Table 1 gives the comparison between experimental and analytical natural frequencies, for the first two modes, obtained from both the studies. There are differences between analytical FE model predictions and experimental results, which is due to assumptions and approximations involved in the FE model. Thus the FE models need to be updated. However, the differences between the corresponding results of both studies are minor.

Apart from natural frequency comparison (as given in Table 1), another method of model correlation is mode shape comparison. To compare the mode shapes, we plot the deformed shapes of the structure for a particular mode, using experimental as well as analytical model. These mode shapes are plotted side-by-side for quick comparison. This is a graphical approach to model correlation. Mode shape corresponding to second mode is shown in Fig. 6, using ICATS software. It shows a fairly good level of correlation between the experimental and analytical FE model.

Several researchers have developed techniques for quantifying the comparison between measured and predicted mode shapes. As an alternative to the graphical approach, Model Assurance Criterion i.e. MAC, [15]) is a widely used technique to estimate the degree of correlation between mode shape vectors. This provides a measure of the least squares deviation

![Fig. 6. Mode shape comparison.](image)
or 'scatter' of the points from the straight-line correlation. The MAC between a measured and analytical mode is:

\[
MAC(a,\hat{a}) = \frac{1}{\left(\mathbf{U}^T\mathbf{U}\right)^{1/2}}\left(\mathbf{U}^T\mathbf{a}\right)^T\left(\mathbf{U}^T\mathbf{a}\right)
\]

where \(a\) and \(\hat{a}\) represents measured or experimental and analytical mode shapes respectively. MAC is a scalar quantity whose value is between 0 and 1. A value of MAC close to 1 shows a good degree of correlation between experimental and analytical FE model. We can see in Table 1 that the MAC numbers are close to 1, though somewhat lower for the second mode. Table 1 also shows that the results obtained from both the studies are quite close to each other.

5. Finite element model updating

Model updating can be defined as 'the process of correcting the numerical values of individual parameters in a analytical FE model using data obtained from an associated experimental model such that the updated model correctly describes the dynamic properties of the subject structure'.

Various model updating methods can be classified into two major groups:

- Direct matrix methods
- Indirect or iterative methods

Direct methods are capable of reproducing measured data exactly, but they provide no opportunity for the user to select parameters for updating. Here parameter means any physically realizable quantity like Young's modulus, Poisson's ratio, mass density etc. When using the direct methods, the entire stiffness and mass matrices are updated in a single (non-iterative) solution step. Then, the individual matrix terms all get changed without any regard for the change in element shape or size. Consequently any physical meaning, which the initial finite element model might have possessed, is lost in the updating process.

Techniques like the indirect methods, allow the updating parameters to be selected. So, considerable physical insight is required if the model is to be improved, not only in its ability to reproduce test results, but also in interpreting the parameters physically. Methods in this second group are iterative and, as such, considerably more expensive of computer effort.

Two studies have been carried out for model updating and computer programs for the same were developed in the present work using MATLAB. In the first study, two direct methods are applied to update the analytical FE model of the drilling machine structure.

Baruch and Bar-Itzhack [4] and Baruch [5] considered the mass matrix of the analytical model to be exact. The measured eigenvectors are corrected by using the relation:

\[
\phi = \phi_m\left[\phi_m^T\mathbf{M}_a\phi_m\right]^{-1/2}
\]
The stiffness matrices of the analytical FE model after updating is given as:

$$K_u = K_a - K_a \phi \phi^T M_a + M_a \phi \phi^T K_a + M_a \phi \phi^T M_a$$

The derivation is based on the corrected stiffness matrix and should reproduce the measured modal data.

Berman and Nagy [6] 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:

$$\dot{M}_u = \dot{M}_a + \dot{M}_a \phi_{m} \bar{M}_a^{-1}(I - \bar{M}_a)M_a^{-1} \phi_{m}^T M_a$$

$$\bar{M}_a = \phi_{m}^T M_a \phi_{m}$$

The stiffness matrix is updated using following equation:

$$K_u = K_a - K_a \phi \phi^T M_a + \dot{M}_u \phi \phi^T K_a + \dot{M}_u \phi \phi^T M_a$$

Eqs. (3) and (6) are identical. The updated mass matrix obtained will be symmetric and stiffness matrix will be close to that of exact stiffness matrix. Results obtained from Baruch and Berman-Nagy model updating methods are tabulated in Table 2. It is clear from Table 2, that the updated model reproduces the measured frequencies. After updating, MAC values have been calculated again using Eq. (1) and are shown in Table 2. It can be observed that updated MAC values show some improvement over the initial MAC values.

In the second study, the model updating of drilling machine has been carried out using indirect or modal sensitivity method. Modal sensitivity for the selected parameters has been found out using FEMtools software. FEMtools software uses Bayesian parameter estimation [16] technique, which is an iterative method of model updating, and it is sensitivity based parameter estimation technique. The FE model has been updated using sensitivity method. The various parameters selected for updating are:

- Young's modulus of elasticity
- Mass density
- Cross section area
- Bending moment of inertia

Table 2
Comparison of experimental and updated FE frequencies and MAC values

<table>
<thead>
<tr>
<th>Mode number</th>
<th>Study 1</th>
<th>Study 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured frequency</td>
<td>Baruch method</td>
</tr>
<tr>
<td></td>
<td>Updated frequency</td>
<td>MAC</td>
</tr>
<tr>
<td>Mode 1</td>
<td>8.67 Hz</td>
<td>0.925</td>
</tr>
<tr>
<td>Mode 2</td>
<td>47.34 Hz</td>
<td>0.966</td>
</tr>
</tbody>
</table>
The normalised sensitivity has been calculated for the above parameters for both the modes using the above software. With the updating parameters, the model-updating program has been executed for five iteration, with a maximum of 1% variation in the weighted absolute relative difference (CCABSOLUTE) between resonance frequencies.

The results after updating have been tabulated in Table 2. It clearly shows that after updating, the updated FE model closely represents the actual machine tool structure. It also shows that MAC values have also been improved after updating. Table 2 also shows that the updated frequencies for both the cases are quite close to each other for the first mode.

6. SDM studies using updated models for dynamic design

Structural dynamic modification (SDM) techniques are methods by which dynamic characteristics of the structure can be improved by adding the modifications like changing mass, spring, damping etc. The mass modification has been considered here for predicting dynamic characteristics using updated FE model.

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, i.e. node 20 as in Fig. 3. The drilling machine is shown schematically in Fig. 7. The modal test for the mass modified machine is carried out by Modak [10], using impact hammer for excitation. The FRFs are analyzed in ICATS in order to obtain an experimental estimate of the altered dynamic characteristics of the drilling machine, as given in Table 3.

The effect of the same mass modification on the dynamic characteristics of the drilling machine has also been predicted by updated FE model. Table 3 gives a comparison of the predictions based on the updated FE models obtained by direct methods of Baruch, Berman and Nagy and by indirect method based on sensitivity analysis, with that of the measured modified characteristics.
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. Now, this updated FE model has been further used to predict, at computer level, the effect of various mass modifications on the structural dynamics of the drilling machine, for the purpose of dynamic design.

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 node 20 and node 25, on the drilling machine has been considered. The effects on FRFs due to these modifications have been shown in Figs. 8 and 9 respectively. The values of the first two natural frequencies have been predicted using updated FE models and MODIFY module of ICATS software and are shown in Tables 4 and 5. The measured frequencies for modes 1 and 2 for the modified cases were also obtained using a modal exciter as in study 2 and are given in the above tables. The effect of modifications is clearly seen by comparison of the measured values of unmodified cases given in Table 2.

It can be observed the Tables 4 and 5 that the results predicted by various methods are very close to each other. In particular, the sensitivity method has given results very close to the meas-
Further, Figs. 8 and 9 show the regenerated FRF and shift in natural frequencies due to mass modification of 20 kg, at node 20 and 25 respectively, using MODIFY module in ICATS software [11]. Four modes have been included in this study.

Figs. 8 and 9 show that due to mass modification at node 20, there is considerable shift in 3rd and 4th natural frequencies, whereas due to mass modification at node 25, 2nd and 3rd natural frequencies have been shifted considerably.

Table 4
Predicted natural frequencies after mass modification using 20 kg at node 20 (Panel A), predicted natural frequencies after mass modification using 40 kg at node 20 (Panel B)

Comparisons of SDM predictions using updated FE model

<table>
<thead>
<tr>
<th></th>
<th>Baruch method</th>
<th>Berman method</th>
<th>Sensitivity method</th>
<th>ICATS MODIFY</th>
<th>Measured</th>
<th>Frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Panel A</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass modification of 20 kg</td>
<td>8.22 Hz</td>
<td>7.99 Hz</td>
<td>8.2 Hz</td>
<td>8.2 Hz</td>
<td>8.2 Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>47.08 Hz</td>
<td>42.87 Hz</td>
<td>42.8 Hz</td>
<td>42.8 Hz</td>
<td>42.8 Hz</td>
<td></td>
</tr>
<tr>
<td><strong>Panel B</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass modification of 40 kg</td>
<td>7.83 Hz</td>
<td>7.76 Hz</td>
<td>7.75 Hz</td>
<td>7.76 Hz</td>
<td>7.8 Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>46.86 Hz</td>
<td>46.44 Hz</td>
<td>41.27 Hz</td>
<td>4644 Hz</td>
<td>41.3 Hz</td>
<td></td>
</tr>
</tbody>
</table>

The results of these comparisons showed that the updated FE model, obtained from both the studies, can predict the effect of modifications on the dynamic characteristics of the machine with a fair degree of accuracy and the procedure can be used with confidence in order to obtain desired modal frequencies.
Table 5
Predicted natural frequencies after mass modification using 20 kg at node 25 (Panel A), predicted natural frequencies after mass modification using 40 kg at node 25 (Panel B)

Comparisons of SDM predictions using updated FE model

<table>
<thead>
<tr>
<th></th>
<th>Baruch method</th>
<th>Berman method</th>
<th>Sensitivity method</th>
<th>ICATS MODIFY</th>
<th>Measured frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Panel A</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass modification of 20 kg</td>
<td>8.34 Hz</td>
<td>8.44 Hz</td>
<td>8.35 Hz</td>
<td>8.4 Hz</td>
<td>8.4 Hz</td>
</tr>
<tr>
<td></td>
<td>42.24 Hz</td>
<td>41.67 Hz</td>
<td>41.67 Hz</td>
<td>42.2 Hz</td>
<td>41.6 Hz</td>
</tr>
<tr>
<td><strong>Panel B</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass modification of 40 kg</td>
<td>8.03 Hz</td>
<td>8.04 Hz</td>
<td>8.1 Hz</td>
<td>8.1 Hz</td>
<td>8.1 Hz</td>
</tr>
<tr>
<td></td>
<td>38.89 Hz</td>
<td>41.02 Hz</td>
<td>39.15 Hz</td>
<td>39.5 Hz</td>
<td>39.5 Hz</td>
</tr>
</tbody>
</table>

7. Conclusions

Comparison of results obtained from experimental modal analysis and FE models of a drilling machine, indicate that its finite element models need to be updated. This is necessary in order to predict dynamic behavior of the complex structure with an acceptable accuracy.

An experimentation involving modal testing has been carried out on the drilling machine using impact hammer as well as modal exciter. It has been observed that both impact hammer and modal exciter yield good results for fairly complex structures like drilling machine.

Analytical FE model has been updated in the light of experimental data using direct as well as indirect methods. Both the methods give results, which are fairly close when used for predicting results of SDM attaching additional mass on the machine at different locations. The predicted results have been validated by comparison with measured results and are seen to be fairly accurate in particular for the indirect method using sensitivity analysis.

References