Operational Modal Analysis of a Boring Bar During Cutting

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Abstract

Internal turning or boring operation is a common metal working process that is usually associated with vibration problems. Vibration problems in internal turning considerably influence important factors such as surface quality, productivity, production costs, etc. In this paper we report analysis results from an operational modal analysis of a boring bar during cutting operation. The results are compared with operating deflection shape results and traditional modal analysis results of the same boring bar. Results show that the first bending modes in the directions of cutting speed and cutting depth are active in the operating vibrations. The three analysis methods result in similar conclusions.

1 Introduction

In the manufacturing industry, the internal turning or boring operation is a common metal working process that is usually associated with vibration problems. Vibration in boring operations is usually inevitable; to obtain satisfactory workpiece shape and tolerance, and adequate tool-life, the influence of vibration in the process of machining a workpiece must be kept to a minimum. This necessitates extra care being taken in production planning and preparation. Thus, the vibration problems in internal turning considerably influence important factors such as productivity, production costs, etc.

In internal turning or boring the metal cutting process is carried out in pre-drilled holes or holes in cast etc. The dimensions of the workpiece hole will generally determine the length and limit the diameter or cross sectional size of the boring bar. As a result, boring bars are frequently long and slender and thus sensitive to excitation forces introduced by the material deformation process in the turning operation [1]. Thus, the boring bar is usually the weakest link in the boring bar-clamping system of the lathe. The motion or vibration of the boring bar will affect the result of the machining in general and the surface finish in particular. Tool life is also likely to be influenced by vibrations. The vibration pattern of a boring bar is usually dominated by one of two resonance frequencies; these probably correspond to the first two bending resonance frequencies of the clamped boring bar [2, 3]. Generally, the material deformation process in the turning operation excites one of these resonance frequencies; a frequent result of this resonant motion is extremely high boring-bar vibration levels [2]. Furthermore, the boring bar vibration in a continuous boring operation is dominated...
to a great extent by the motion in the cutting speed direction [2].
In order to gain further understanding of the dynamic behaviour of clamped boring bars in the metal cutting process experimental methods may be utilized. For the purposes of experimentation, the dynamic properties of a structure may be investigated by experimental modal analysis, operating deflection shape analysis, ODS and output only modal analysis [4, 5, 6].
This paper investigates the operating deflection shapes, mode shapes and corresponding resonance frequencies for the first two modes of a clamped boring bar. An experimental modal analysis, a operational modal analysis as well as a operating deflection shape analysis of the boring bar have been carried out. The results from the three analyses have then been compared.

2 Materials and Methods

2.1 Experimental Setup

The experimental modal analysis, the operational modal analysis and the operating deflection shape analysis have been carried out in a Mazak SUPER QUICK TURN - 250M CNC turning centre. This has 18.5 kW spindle power and a maximum machining diameter of 300 mm, with 1007 mm between the centres. The cutting operations were performed as an external turning operation using the WIDAX S40T PDUNR15 boring bar.

2.1.1 Measurement Equipment and Setup

The measurements can be divided into two different categories: experimental modal analysis of the boring bar and operational modal analysis together with operating deflection shape (ODS) analysis of the boring bar. For measuring the following measurement equipment has been used: 14 PCB 333A32 accelerometers(modal analysis), 14 PCB U353B11 accelerometers(ODS and operational modal analysis), OSC audio power amplifier, USA 850, Ling Dynamic Systems shaker v201, Brüel & Kjær 8001 impedance head, Brüel & Kjær NEXUS conditioning amplifier 2692, HP VXIE1432 front-end data acquisition unit, PC with IDEAS Master Series version 6 and ARTeMIS Extractor 3.4.

Spatial measurements of the response of the boring bar were made using 14 accelerometers. 7 accelerometers were glued equidistantly to the boring bar in the cutting speed direction and 7 accelerometers were glued equidistantly to the boring bar in the cutting depth direction, see Fig. 1. The ODS and operational modal analysis data were collected using less sensitive accelerometers than those used in the modal analysis measurement. For the ODS and operational modal analysis, the boring bar vibration was measured during a continuous cutting operation.

2.1.2 Work Materials and Cutting Tool

The operating deflection shape measurements were performed during continuous cutting operation in two different work materials: cast iron, SS 0727-02 and chromium molybdenum nickel steel, SS 2541-03. The cutting tool used in the cutting experiments was standard 55° diagonal insert. The geometry was DNMG 150608-SL and carbide grade TN7015.
2.2 Experimental Modal Analysis

Experimental modal analysis is a powerful tool for deriving reliable models representing dynamic properties of structures. It is the process of determining the modal parameters—the natural frequencies, the damping ratios, the mode shapes and the modal scaling—of linear time invariant systems based on estimates obtained from experimental measurements [4, 5, 7]. Experimental modal analysis generally relies on simultaneous measurements of response and excitation force at discrete points on a structure. Consequently, in most cases, experimental modal analysis will automatically model a structure under study as a multiple-degree-of-freedom system [4, 5]. To estimate the two first eigenfrequencies, damping ratios and mode shapes for the clamped boring bar, the polyreference least squares complex exponential time domain method was used; this is described in [4].

The parameters used in the modal analysis of the clamped boring bar can be found in [3].

2.3 Operating Deflection Shape Analysis

To obtain statistically reliable frequency domain information concerning the phase and amplitude of the response signals from $N$ discrete points of an operating structure which is sufficient in order to produce an estimate of $\{ODS(f)\}$, cross power spectrum estimates and power spectrum estimates may be used [8, 9]. In estimating spectral properties of a signal it is important to select an appropriate scaling of the spectrum estimator [8, 9]. The spectrum estimates may be scaled for either the tonal components of a signal—power spectrum (PS) estimates— or the random part of a signal—power spectral density (PSD) estimates—[8]. The square root of the power spectra, $\sqrt{\hat{P}_{nn}(f)}$, $n \in \{1, \ldots, N\}$ may be produced. By combining these spectra with the phase functions $\hat{\theta}_{n1}(f)$, $n \in \{2, \ldots, N\}$ of the cross spectra $\hat{P}_{n1}(f)$, $n \in \{2, \ldots, N\}$, an estimate of the frequency domain operating deflection shape may thus be constructed as follows [3]:

$$\{ODS(f)\}_{RMS} = \left\{ \sqrt{\hat{P}_{11}(f)} \sqrt{\hat{P}_{22}(f)} e^{i\hat{\theta}_{21}(f)} \ldots \sqrt{\hat{P}_{NN}(f)} e^{i\hat{\theta}_{N1}(f)} \right\}^T$$

(1)
Table 1: Cutting data used in the operating deflection shape measurements.

<table>
<thead>
<tr>
<th>Workpiece material</th>
<th>Cutting speed (v), (m/min)</th>
<th>Cutting depth (a), (mm)</th>
<th>Feed rate (s), (mm/rev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS 0727-02</td>
<td>200</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>SS 2541-03</td>
<td>75</td>
<td>2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 1: Cutting data used in the operating deflection shape measurements.

Here \(u(x_1, t)\) has been used as reference signal.
The workpiece material and the cutting data used are summarized in Table 1; the parameters used when obtaining the data for the ODS analysis can be found in [3].

### 2.4 Operational Modal Analysis

Output only modal analysis -the estimation of natural frequencies, damping ratios and mode shapes for a operating structure- may be carried out based on an estimate of the power spectral density matrix \(\hat{P}_{uu}(f)\) for the response signals from \(N\) discrete points of the operating structure. The power spectral density matrix \(\hat{P}_{uu}(f)\) is defined in [9, 6]. For a lightly damped structure the power spectral density matrix \(\hat{P}_{uu}(f)\) may be approximated as [6]

\[
[\hat{P}_{uu}(f)] = \frac{1}{2\pi} \sum_{n \in \text{Sub}(f)} \frac{d_n \{\psi\}_n \{\psi\}_n^T}{j f - (-f_n \xi_n + j f \sqrt{1 - \xi_n^2})} + \frac{d_n^* \{\psi^*\}_n \{\psi^*\}_n^T}{j f - (-f_n \xi_n - j f \sqrt{1 - \xi_n^2})},
\]

(2)

where \(n \in \text{Sub}(f)\) is the set of modes that have an significant contribution to the responses at frequency \(f\), \(\{\psi\}_n\) are the modal vectors, \(f_n\) are the undamped system’s eigenfrequencies, \(\xi_n\) are the modal damping ratios and \(d_n\) are the modal proportionality constants [6]. By using the singular-value decomposition (SVD) at the discrete frequencies of a FFT based estimate of the power spectral density matrix, estimates of natural frequencies, damping ratios and mode shapes for the structure may be produced [6]. To estimate the first eigenfrequency, damping ratio and mode shape for the clamped boring bar, the Enhanced Frequency Domain Decomposition natural input modal analysis parameter extraction algorithm was used [6, 10].
The workpiece material and the cutting data used are given in row 2, Table 1.

### 3 Results

The experimental modal analysis was carried out for the boring bar, clamped using epoxy glue to join the steel wedges inbetween the clamping house and the boring bar, with simultaneous excitation of both the cutting speed and the cutting depth direction. The excitation force was applied by a shaker via an impedance head at 45° angle to both the cutting speed direction and the cutting depth direction. The estimates obtained of the eigenfrequencies and the corresponding damping are given in Table 2. In the modal analysis the coherence values for the involved transfer paths at each eigenfrequency were greater or equal to 0.997. The two mode shape estimates are presented by 2-D plots as their respective contribution to the third dimension was negligible. Fig. 5 a) shows the estimated mode shape of mode 1 at 570 Hz; the estimated mode shape of mode 2 at 595 Hz is shown in Fig. 5 b).

In order to gain further insight into the actual spatial motion of the boring bar during continuous cutting operations, an operating deflection shape analysis was carried out. The boring bar vibration is normally dominated by one of two resonance frequencies in the frequency interval between 500
Hz and 650 Hz. At low cutting speeds below approximately 150 m/min, the first resonance peak, the resonance peak with the lowest frequency of the two dominating peaks, is active. At higher cutting speeds, the second resonance peak is active. Power spectral density estimates of boring bar vibration dominated by the first resonance frequency at approximately 536 Hz are presented in Fig. 3 for the cutting speed direction. The boring bar vibration was excited by a continuous cutting operation in SS 2541-03, feed rate $s = 0.1$ mm/rev, cutting depth $a = 2$ mm, cutting speed $v = 75$ m/min. If the cutting speed is increased so that it exceeds approximately 150 m/min, the dominating frequency of the boring bar vibration spectral density is shifted upwards in frequency to approximately 588 Hz. This is illustrated in Fig. 4 which present spectral density estimates for boring bar vibration in the cutting speed direction during a continuous cutting operation in SS 0727-02, feed rate $s = 0.1$ mm/rev, cutting depth $a = 2$ mm, cutting speed $v = 200$ m/min. Observe the sidebands of the resonance frequency at 588 Hz in the power spectral densities presented in Fig. 4. This indicates that force modulation probably affects the boring bar motion during the machining process. The operating deflection shape of the boring bar at 555 Hz was extracted. In Fig. 5 a), the operating deflection shape at 555 Hz is presented.

Preliminary results of parameter extraction using the Enhanced Frequency Domain Decomposition natural input modal analysis parameter extraction algorithm. The first bending mode was found in the cutting speed direction and is shown in Fig. 5 b) The estimates of the resonance frequencies of the boring bar produced by the three analysis methods are given in Table 4.
Figure 3: Power spectral density estimate of the dynamic response of the boring bar in the cutting speed direction during a continuous cutting operation in SS 2541-03, $s = 0.1$ mm/rev, $a = 2$ mm, $v = 75$ m/min, tool DNMG 150608-SL, grade 7015.

Figure 4: Power spectral density estimate of the dynamic response of the boring bar in the cutting speed direction during a continuous cutting operation in SS 0727-02, $s = 0.1$ mm/rev, $a = 2$ mm, $v = 200$ m/min, tool DNMG 150608-SL, grade 7015.[3]

Table 3: Frequency and damping estimates in the output only modal analysis.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Damping ratio [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>555</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 4: Resonance frequencies of the boring bar obtained using the three different analysis methods.
Figure 5: a) estimate of the operating deflection shape of the boring bar motion at 555 Hz and b) operational mode shape estimate of mode 1 at 555 Hz, during a continuous cutting operation in SS 2541-03, $s = 0.1$ mm/rev, $a = 2$ mm, $v = 75$ m/min, with cutting tool DNMG 150608-SL, grade 7015.

## 4 Conclusions and Future Work

The experimental modal analysis of the boring bar with modified clamping resulted in two identified modes. The first mode in the cutting depth direction had a resonance frequency of 570 Hz, and a relative (viscous) damping of 1.85%. The second mode in the cutting speed direction had a resonance frequency of 595 Hz and a damping of 0.84%. The damping of the first mode was noted to be slightly larger than prior to the modification of the clamping [3].

From the Power Spectrum Density results, it is apparent that vibrations of the boring bar are dominating in the cutting speed direction during a continuous cutting operation (see Figs. 3 and 4). The deformation pattern of the boring bar is according to the ODS measurement dominating in the cutting speed direction at the resonance peak at 555 Hz, (see Fig. 5). The reason is probably that the boring bar is mainly excited in the cutting speed direction. From the preliminary operational modal analysis the first mode in the cutting speed direction had a resonance frequency of 555 Hz, and a relative (viscous) damping of 0.55%. Of significance for the operational modal analysis is the estimate of the relative damping. The results are not consistent between the experimental modal analysis and the ODS together with the operational modal analysis, and should be further analysed in future work. However, the results can possibly be explained by the change in the directions of the modes between the unmodified and the modified clamping case. Furthermore, operational modal analysis seems to be a promising method that is likely to enable further understanding of e.g. the dynamic behaviour of clamped boring bars in the metal cutting process.

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References


