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INVESTIGATION OF THE DYNAMIC PROPERTIES OF A BORING BAR CONCERNING DIFFERENT BOUNDARY CONDITIONS

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Abstract

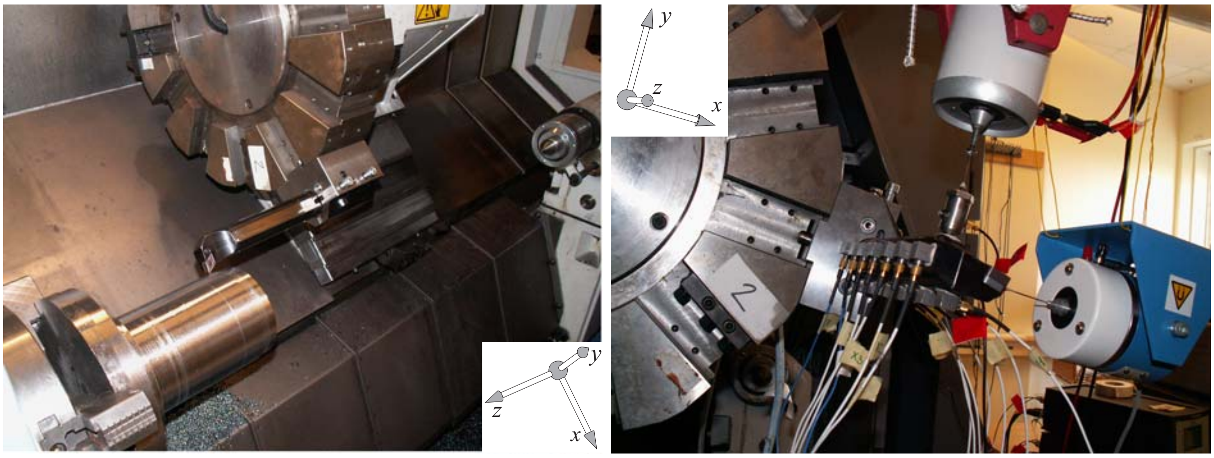
The boring bar is one of the most widely used types of tool holder in metal cutting operations. The turning process subjects the tool to vibration, and cutting in deep workpiece cavities is likely to result in high vibration levels. The consequences of such vibration levels are generally; reduced tool life, poor surface finishing and disturbing sound. Internal turning frequently requires a long and slender boring bar in order to machine inside a cavity, and the vibrations generally become highly correlated with the fundamental bending mode of the boring bar. Different methods can be applied to reduce the vibrations, the implementation of the most efficient and stable methods require in-depth knowledge concerning the dynamic properties of the tooling system. Furthermore, the interface between the boring bar and the clamping housing has a significant influence on the dynamic properties of the clamped boring bar. In this paper different cases of boundary condition of the boring bar are presented partly analytically but also experimentally. This paper focuses on dynamic properties of a boring bar that arise due to different clamping conditions of the boring bar introduced by a clamping housing commonly used in the manufacturing industry.

1. INTRODUCTION

The problem of boring bar vibration can be addressed using conventional methods, such as redesigning the machine tool system, implementing tuned passive damping or implementing active control [1, 2]. However, the order of stability improvement achieved usually correlates to the quality and extent of knowledge of the dynamic properties of the tooling structure - the interface between the cutting tool, or insert, and the machine tool. Boring bar vibrations are usually directly related to the lower order bending modes and the dynamic properties of a boring bar installed in a lathe are directly influenced by the boundary conditions, i.e. the clamping of the bar [3]. It appears that little work has been done on the clamping properties' influence on the dynamic properties of a clamped boring bar [4]. Thus, it is of significance to investigate the clamping properties' influence on the dynamic properties of the clamped boring bar in order to gain further understanding of the dynamic behavior of clamped boring bars in the metal cutting process. This paper focuses on the variation in the dynamic properties of a clamped boring bar imposed by controlled discrete variations in the clamping conditions produced by a standard clamping housing of the variety commonly used in industry today.

2. MATERIALS AND METHODS

The experimental setup and subsequent measurements were carried out in a Mazak SUPER QUICK TURN - 250M CNC turning center, presented by the photo in Figure 1. A coordinate system was defined: z in the feed direction, y in the reversed cutting speed direction and x in the direction of cutting depth, see Figure 1 a) and b). The boring bars were positioned in the operational position, mounted in a clamping housing attached to a turret with screws, during all measurements. The turret may be controlled to move in the cutting depth direction, x-direction, and in the feed direction, z-direction, as well as to rotate about the z-axis for tool change.



a) b)

Figure 1. a) The room in the Mazak SUPER QUICK TURN - 250M CNC lathe where machining is carried out, b) the experiment setup.

2.1. Measurement Equipment and Setup

Twelve accelerometers and two cement studs for the impedance heads were attached onto the boring bars. The sensors were evenly distributed along the centerline, on the under-side and on the back-side of the boring bar; six accelerometers and one stud on the respective side (see Figure 1). To excite all the lower order bending modes, two shakers were attached via stinger rods to the impedance heads, one in the cutting speed direction (y-) and the other in the cutting depth direction (x-) see Figure 1. The excitation positions were relatively close to the cutting tool [4]. Data was collected using a VXI Mainframe and I-DEAS software.

2.2. Boring Bar, Clamping Housing and Clamping Conditions

The boring bar used in the modal analysis was a standard boring bar, WIDAX S40T PDUNR15F3 D6G presented in Figure 2, manufactured in the material 30CrNiMo8, (AISI 4330) which is a heat treatable steel alloy. The clamping housing was a basic 8437-0 40mm Mazak holder, presented in Figure 2, and clamps the tool holder by means of either four: two from the top and two from bottom. The basic holder itself is mounted onto the turret with four screws. In the first setup, the standard boring bar was clamped using four M8 class 8.8 screws. The screws were tightened first from the top and then from the underside. Secondly, in order to accomplish a linearized clamping condition, the standard clamping was modified. A boring bar WIDAX S40T PDUNR15F3 D6G, the same model as the standard boring bar, was used together with three steel wedges. The steel wedges were shaped geometrically to render a circular cross section on the boring bar along its clamped end. The boring bar end with circular cross section was pressed into the clamping housing and glued to it with epoxy to make the clamping rigid, see Figure 2.

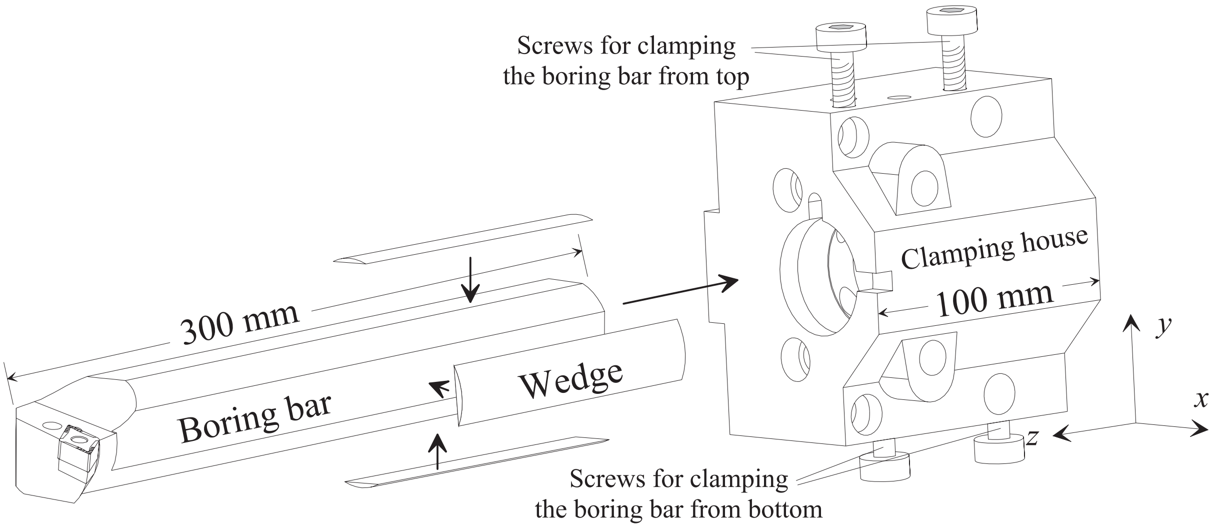


Figure 2. The boring bar and how it is positioned in the clamping housing, the standard way of clamping uses screws and the linearized setup uses steel wedges glued to the boring bar.

2.3. Modal Analysis

The modal parameters where estimated in I-DEAS using polyreference least square complex exponential method developed by Vold [5], in time domain for the poles and frequency domain for the mode shapes. In order to reduce the effect of leakage Burst Random was used as excitation signal with settings of 90%, 10% of the burst and dead period respectively.

2.4. Multi-span Euler Bernoulli Boring bar with Elastic Foundation

A three span Euler-Bernoulli beam incorporating clamping flexibility through the use of transverse springs and rotational springs may be used for the modeling of a clamped boring bar [4]. If the clamping housing is considered to be a rigid body, and letting the clamping screws be deformable bodies, this will yield "elastic supports" [6] as a boundary condition. The elastic support can be seen as two springs connected to one point, one spring in the transverse direction; thus, transverse stiffness resistance k_T and one rotational spring exhibits rotational stiffness resistance k_R. The configurations of the "elastic support" condition are presented in Figure 3.

The spring coefficients k_T and $k_R$are derived from the material properties, the dimensions and the boundary conditions of the screws [4].

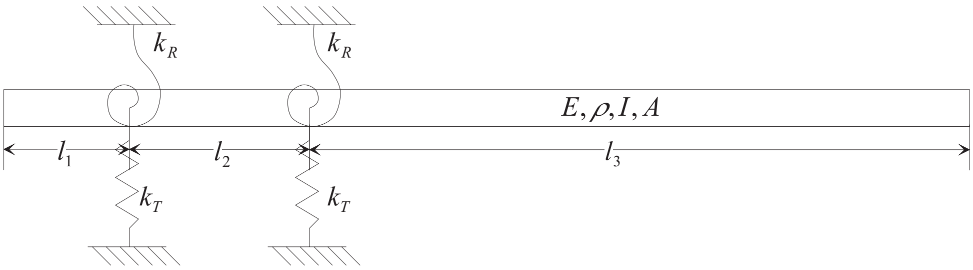


Figure 3. a) A model of a three span beam with elastic support, b) a model of a four span beam with elastic support, where E is the elasticity modulus (Young's coefficient), ρ the density, A the cross-sectional area, I the moment of inertia, k_T the transverse spring coefficient, k_R the rotational spring coefficient the length of the different spans in mm are $l_1 = 35$, $l_2 = 50$ and $l_3 = 215$.

3. RESULTS

The first results are from the standard boring bar firstly clamped such that the bottom side of the boring bar is clamped against the clamping housing (i.e. the screws are tightened from the topside first and subsequently from the bottom-side) the fundamental boring bar resonance frequencies increases with increasing tightening, see Figure 4 a). By changing the excitation lev-

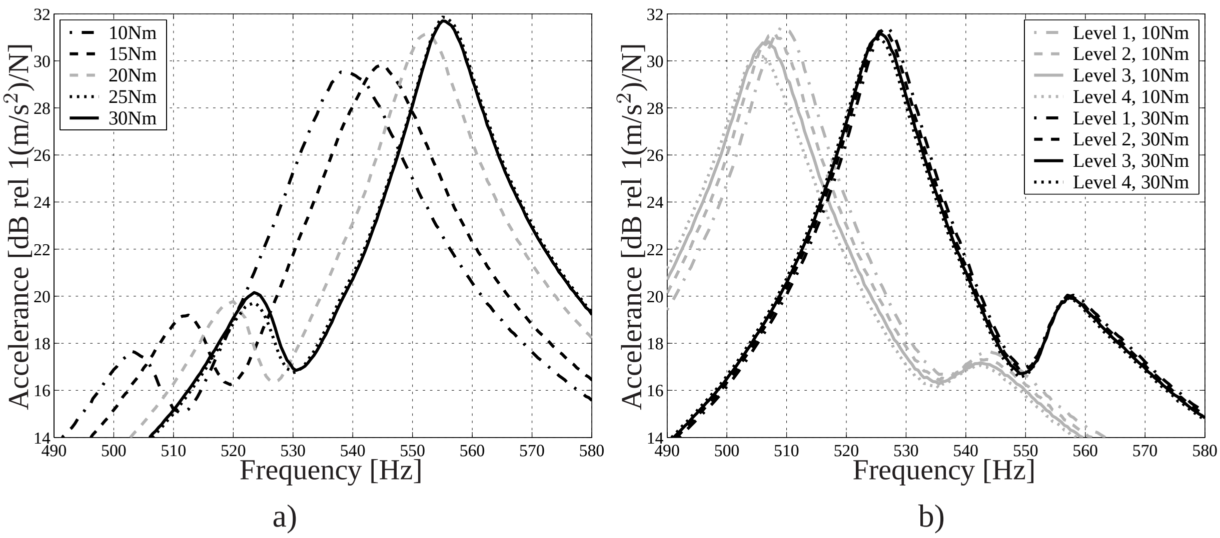


Figure 4. The accelerance of the boring bar response using the standard boring bar, four screws of size M8 and when clamp screws were tightened firstly from the upper-side. a) the driving point in cutting speed direction (y-) using five different tightening torques b) the driving point in negative cutting depth direction (x-) for two tightening torques and four excitation levels.

els, nonlinearities in the dynamic properties of the boring bar might be observable via changes in frequency response function estimates for the same input and output locations at the boring bar. As can be seen in Figure 4 b) the fundamental boring bar resonance frequencies decreases slightly with increased excitation level. The estimated resonance frequencies and relative damping from all 20 measurements are presented in Table 1 and Table 2.

Table 1. Estimates of the fundamental boring bar resonance frequencies based on all the measurements using the setup with standard boring bar, clamped with four screws first tightened from the upper-side of the boring bar.

	Resonance Frequency, Mode 1 [Hz]				Resonance Frequency, Mode 2 [Hz]			
Torque	Level 1	Level 2	Level 3	Level 4	Level 1	Level 2	Level 3	Level 4
10Nm	509.52	507.87	506.61	505.51	540.86	540.15	539.33	540.07
15Nm	518.13	516.50	515.23	514.18	546.50	546.31	545.73	544.60
20Nm	523.84	522.97	522.13	521.55	553.01	552.86	552.49	552.13
25Nm	526.64	526.05	525.50	525.10	556.07	555.84	555.66	555.42
30Nm	526.72	526.23	525.79	525.45	555.67	555.68	555.55	555.35

Table 2. The relative damping estimates for the fundamental boring bar bending modes based on all the measurements using the setup with standard boring bar, clamped with four screws first tightened from the upper-side of the boring bar.

	Damping of Mode 1 [%]				Damping of Mode 2 [%]			
Torque	Level 1	Level 2	Level 3	Level 4	Level 1	Level 2	Level 3	Level 4
10Nm	0.99	1.04	1.08	1.14	1.31	1.33	1.46	0.26
15Nm	0.97	1.00	1.03	1.08	1.26	1.32	1.28	1.23
20Nm	0.88	0.91	0.94	0.96	1.04	1.04	1.01	0.99
25Nm	0.87	0.88	0.90	0.92	0.97	0.93	0.91	0.90
30Nm	0.86	0.88	0.90	0.93	0.97	0.95	0.92	0.90

A boring bar mode shape shows the spatial deformation pattern of the bar for that particular mode and thus for each degree of freedom measured on the boring bar, in both amplitude and spatial phase. First, results are presented from the standard boring bar, tightening clamp screws firstly from the upper-side. The shapes are presented in zy-plane and xy-plane in Figure 5. The angle of rotation around z-axis (relative the cutting depth direction for each measurement) is presented in Table 3. The mode shapes in xy-plane illustrated in Figure 5 and the corresponding values in Table 3 show an average rotation of approximately 20 degrees.

Table 3. Angle of mode shapes for the standard boring bar, relative to cutting depth direction axis.

	Angle of Mode 1, [Degree]				Angle of Mode 2, [Degree]			
Torque	Level 1	Level 2	Level 3	Level 4	Level 1	Level 2	Level 3	Level 4
10Nm	-17.55	-17.10	-16.33	-17.81	-107.13	-106.89	-106.68	-106.43
15Nm	-21.42	-20.84	-20.44	-20.13	-110.30	-109.80	-109.45	-109.22
20Nm	-22.09	-21.81	-21.33	-21.08	-110.96	-110.30	-109.92	-109.76
25Nm	-21.31	-20.90	-20.66	-20.48	-109.90	-109.65	-109.42	-109.32
30Nm	-22.54	-22.27	-22.04	-21.84	-110.92	-110.68	-110.45	-110.35

The results from the linearized clamping are presented in Figure 6 and Table 4. Only a slight variation in the boring bar's resonance frequencies and damping might be observed.

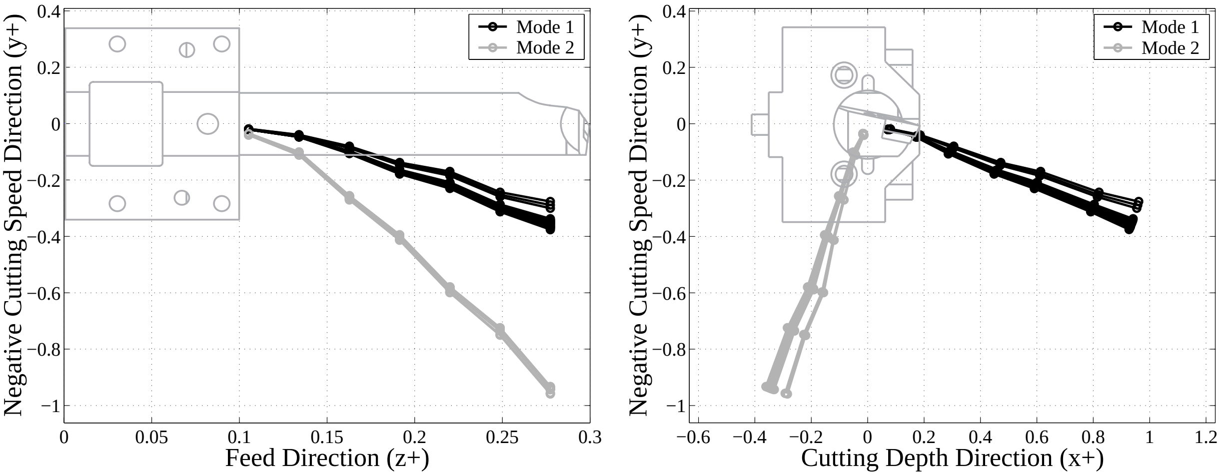
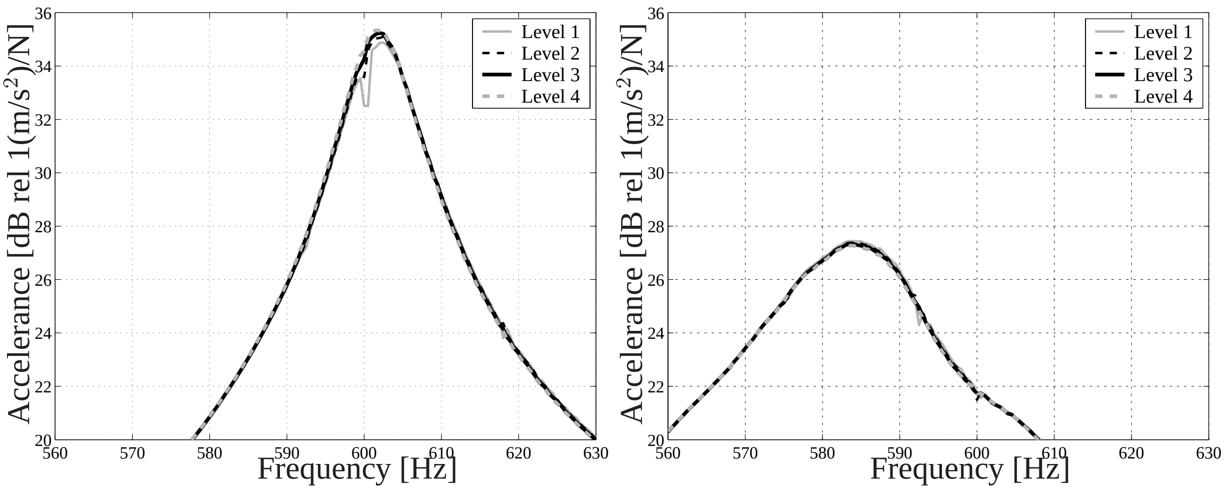


Figure 5. The two first mode shapes of the standard boring bar clamped with four M8 screws, when the clamp screws were tightened firstly from the upper-side, for five different tightening torques and four different excitation levels.

Unfortunately, both resonance frequencies coincide with periodic disturbances originating from the engines in the lathe. One disturbance was at approximately 591 Hz and the other disturbance at approximately 600 Hz. These disturbances will have different influences on the estimates, depending on the excitation level, this may be observed near the peak in Figure 6.



a) b)

Figure 6. The accelerance of the boring bar response using the linearized setup and with four different excitation levels. a) the driving point in cutting speed direction (Y-) and b) the driving point in negative cutting depth direction (X-).

The linear setup, yields almost identical mode shapes as those produced from standard setup , using screws; see Figure 5 and Figure 7. In the xy-plane the shapes only have a rotation of approximately 10 degrees.

The Euler-Bernoulli multi-span model of the boring bar are assumed to have a homogenous constant cross-section, i.e. $E(z) = E$, $\rho(z) = \rho$ $A(z) = A$, $I_x(z) = I_x$ and $I_y(z) = I_y$. The first three resonance frequencies are presented in Table 5 and the corresponding mode shapes are illustrated in Figure 8.

Table 4. The resonance frequency and the relative damping of the linearized boring bar, estimated with poly-reference technique and the angle of rotation around z-axis (relative the cutting depth direction).

Mode 1	Modal Parameters, mode 1				Modal Parameters, mode 2			
	Level 1	Level 2	Level 3	Level 4	Level 1	Level 2	Level 3	Level 4
Frequency [Hz]	583.82	584.15	583.13	582.52	602.25	602.07	601.92	601.79
Damping [%]	2.12	2.04	2.16	2.16	0.76	0.75	0.75	0.74
Angle [Degree]	-7.98	-8.46	-8.05	-8.11	-99.72	-100.00	-99.82	-100.07

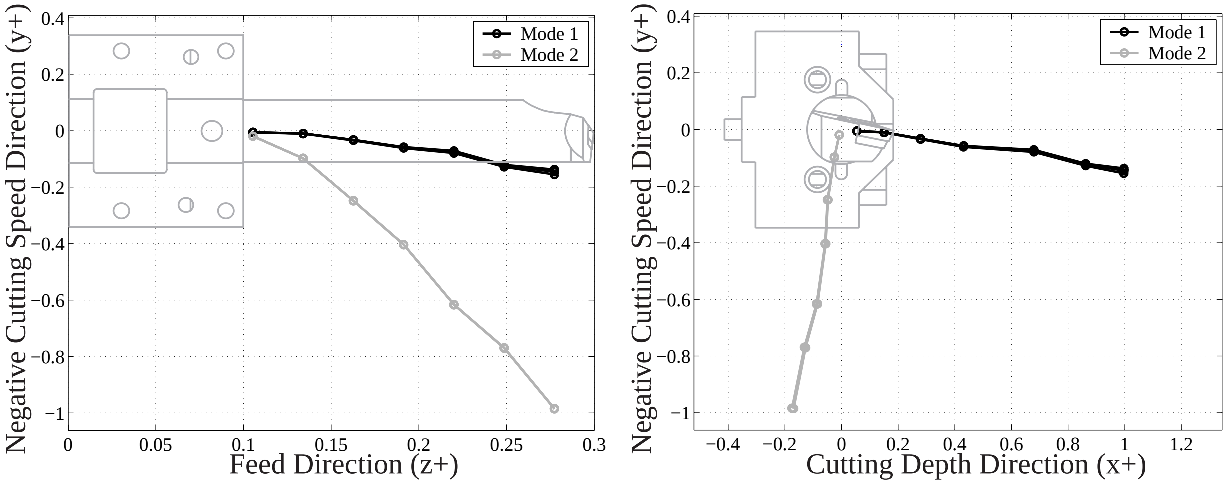


Figure 7. The two first mode shapes of the linearized boring bar for four different excitation levels.

Table 5. The first three resonance frequencies in the cutting speed direction (CSD) and in the cutting depth direction (CDD), for the multi-span boring bar model, with flexible clamping boundary conditions.

Mode in	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]
Cutting Speed Direction (y-)	519.43	3303.79	9257.16
Cutting Depth Direction (x-)	519.27	3302.81	9254.48

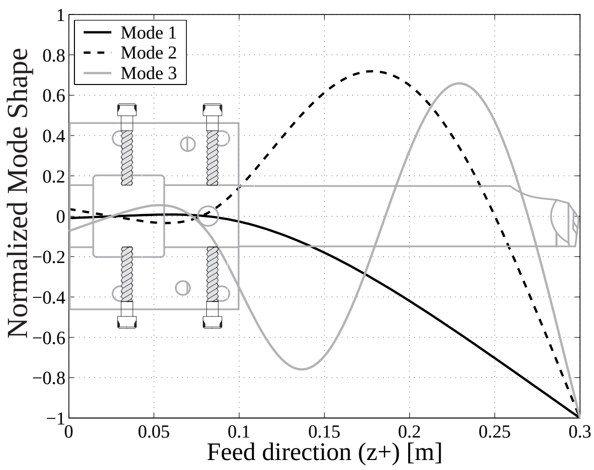


Figure 8. The first three mode shapes for the Euler-Bernoulli boring bar model, with boundary condition free-spring-spring-free

4. SUMMARY AND CONCLUSIONS

The results from the experimental modal analysis of boring bars demonstrate that a boring bar clamped in a standard clamping housing with clamping screws has a nonlinear dynamic behavior. For different clamping screw tightening torques, a boring bar is likely to display different dynamic properties, see Figure 4 a). Furthermore, it is also likely that a boring bar display different dynamic properties each time it is clamped [4]. The clamp screw tightening torque appears to affect the nonlinear behavior of the boring bar. Variation in the FRF:s which was introduced by the four different excitation force levels seems to be larger for a low tightening torque (10Nm) than for a high tightening torque (30Nm), see, for example, Figure 4 b). A trend may be observed; the fundamental boring bar resonance frequencies decrease with increasing excitation level. The experimental modal analysis results from the boring bar clamped in a "linearized" standard clamping housing indicated a significant reduction in non-linear dynamic behavior. By examining the driving point accelerances in the boring bar with "linearized" clamping for the four excitation force levels (see Figure 6), it can be seen that only insignificant differences are present. The Euler-Bernoulli multi-span boring bar model provide rough approximations of the low-order resonance frequencies and the corresponding spatial shapes of the modes. Furthermore, the Euler-Bernoulli model yields a 0.2 Hz difference in frequency between the two fundamental resonance frequencies, while, the experimental results from, for example, the linearized boring bar setup displays a 20-30 Hz difference in fundamental resonance frequencies.

5. ACKNOWLEDGMENTS

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