VIBROACOUSTIC ANALYSIS AND SYNTHESIS OF STRUCK METAL BARS USING MUSICAL INSTRUMENT MODELING TECHNIQUES

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Abstract

The objective for this research is to gain understanding of the sound generation of various bar geometries and impact types. First, the object under investigation was struck using a controllable and repetitive excitation method. The vibration properties of the bar, both longitudinal and transversal, were then measured using both strain gauges and microphones. The recorded signals were analyzed in the frequency-domain to find out which spectral components contributed to the sound generation of the bar. Measurements were carried out at the anechoic chamber of Department of Signal Processing and Acoustics in Aalto University. A computational model was developed based on the measured data. This model can be used to simulate vibration and sound generation on a specific point of the modeled bar. The computational model was constructed using current knowledge on physical modeling of musical instruments, utilizing techniques such as digital waveguides and allpass filters. The results of this study can be generalized and can be used in design and virtual prototyping of tools/working machines that generate transversal vibrations such as rock drills, hand-held machines, jack hammers, pile drivers.

1 INTRODUCTION

There are plenty of applications where impact energy is transmitted along steel bars to a surface to be impacted such as rock drilling equipment, breaking hammer tools, pile drivers, smaller hand held. As steel bars are suitable transmission lines for longitudinal power waves, a major side effect exists, the noise. Striking a metal bar with a metal object is known to be inherently noisy process. Typically a majority of the sound output is generated by the steel bar that is used to transmit the energy of piston impacts as compressive pulses along the steel bar to the desired object. The majority of the sound output is caused by the transversal vibrations that are generated as an unwanted side product of the main process. The non-parallel impacts are causing the generation of the transversal vibrations[1, 2]. Steel bar vibrations are divided to three categories based on the nature of the wave propagation, namely longitudinal, transversal, and torsional [3]. The amount of transversal vibrations with respect to longitudinal is dependent on various phenomena in the process [1]. Typically transversal vibrations are excited by non-parallel impacts [4]. Torsional vibrations propagate at extremely high frequencies (in the MHz range), and are not generally involved in audible sound output [5].

As the noise regulations are getting stricter and as the general awareness of noise reduction as an increased work environment safety procedure is increasing, there is a demand for deeper understanding of the vibration phenomena in such equipment. The gained understanding of the vibration properties of the steel bars can be used in various instances in noise reduction process.

This study presents an analysis of the steel bar vibration and based on the results a vibration model is constructed. Using such model can be beneficial in design and early prototyping of less noisy machinery parts. Results of the study can be exploited in design process of machine parts that are producing transversal vibrations.

This paper is organized as follows, first the basics of the steel bar vibrations is presented in Section 2. Then, measurements that were conducted during vibroacoustic analysis presented in Section 3. Next, a model for stress wave modeling is presented in Section 4. Finally conclusions are drawn in Section 5.

2 WAVE SPEED AND MODAL FREQUENCIES FOR STEELS BARS

The following formulation follows the presentation in [2]. The longitudinal wave speed C_{L} in a material is determined by the material dependent parameters Young's modulus E and material density ρ

$$C_{\mathrm{L}} = \sqrt{E/\rho}. \tag{1}$$

The frequency dependent transversal wave speed C_{T} can be formulated

$$C_{\mathrm{T}} = \sqrt{(\pi/2)(df_b C_{\mathrm{L}})}, \tag{2}$$

where d is the steel bar diameter, f_b is the transversal wave frequency. The longitudinal modal frequencies for a steel bar length of L_{r} is given by

$$f_{Ln} = \frac{nC_L}{2L_r}, \tag{3}$$

where n is the mode index. Modal frequencies of the transversal vibrations in a steel bar can be found frequencies where the steel bar length L_r is a half of the wavelength. The transversal modal frequencies of a steel bar can be determined based on the physical dimensions by

$$f_{Bn} = \frac{n^2 \pi d C_L}{8L_r^2}\left[1 - 1.2\left(\frac{nd}{L_r}\right)^2\right]\left(\frac{2n+1}{2n}\right)^2. \tag{4}$$

The middle correction term (inside square brackets) is the correction term to take into account the rotary inertia and the shear force using the Timoshenko beam theory. The Timoshenko correction factor should be applied when $nD/L_r < 0.4$ .The last term of the Equation is the steel bar end condition correction factor for free-free (F–F) end conditions.

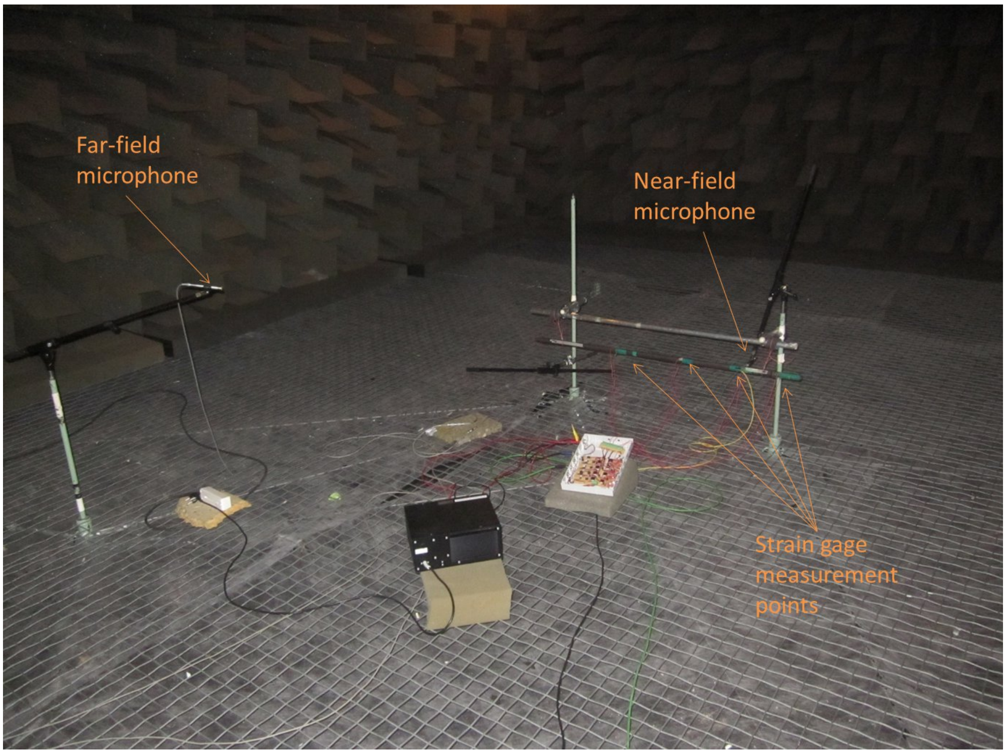


Figure 1: *Overall view of the measurement setup placed inside the anechoic chamber. The steel bar under investigation is rigged to the mounting frame. The audio signals are captured using near- and far-field microphones.*

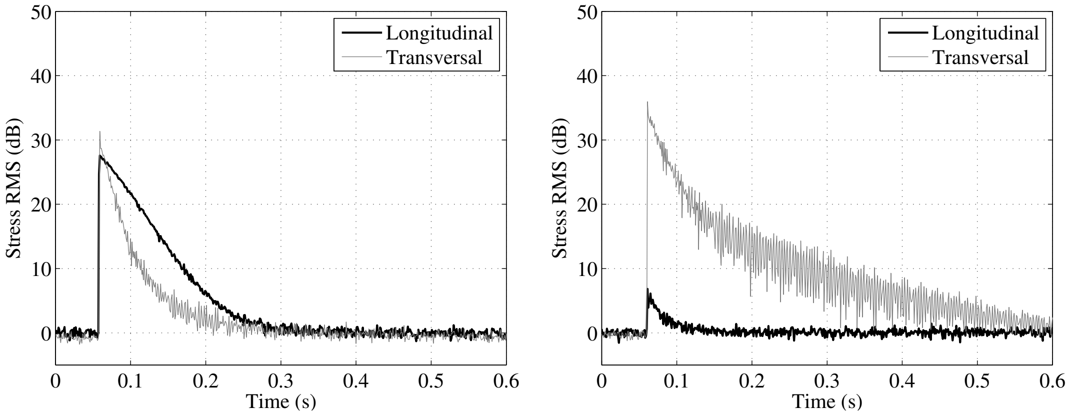
3 VIBROACOUSTIC MEASUREMENTS

3.1 Acoustical Measurements

Acoustical measurements were carried out simultaneously with the strain wave measurements. The microphones were placed in the proximity of the excited objects (See Fig. 1). Measurement equipment consisted of B&K 4191 microphones, B&K 2669 pre-amplifiers and B&K Nexus 2690 microphone condition amplifier. The audio measurement equipment was connected to a RME FireFace 400 audio interface.

3.2 Strain and Stress Wave Measurements

A strain gage is a resistive component which is tightly attached to the surface of the object under investigation. When the object is exposed to compressive or tensile loading the strain gage resistance will change slightly based on the gage length variation. The change in resistance can then be monitored with a Wheatstone bridge circuit and a signal conditioning amplifier.



(a) (b)

Figure 2: *RMS value as a function of time of the measured steel bar strain gage signals. Background noise level is normalized to 0 dB level. (a) Longitudinal impact (b) Transversal impact.*

3.3 Measurement Procedure

Measurements were conducted at the Department of Signal Processing and Acoustics. The large anechoic chamber was used during the measurements. The overall view of the measurement arrangements is presented in Figure 1 where a steel bar is being measured. The steel bar is attached to a custom-made holder which consists of aluminium tubes filled with insulation foam to damp the structure vibrations. The bar holder is attached to the permanently installed vertical poles inside the anechoic chamber. The steel bar in mounted on the holder at two points using thread and neoprene dampers. Neoprene dampers are used to isolate vibration transmission between the steel bar and the holder.

The steel bar was excited by hitting it at the end with a hand-held impact device. The excitation signal is only repeatable to some extent. More reliable results could be achieved using a device which could produce more repeatable impacts.

3.4 Measurement Results

The measured envelopes for longitudinal and transversal vibrations for a longitudinal impact is presented in Figure 2(a) and for transversal impact in Figure 2(b). The longitudinal vibrations are decaying linearly and transversal vibrations exponentially. An example of measured strain waves is presented in Figure 3(a). The upper plot shows the longitudinal strain waves. The shape of the longitudinal strain waves stays a rather constant as the waves reflect back and forth from the steel bar ends. The shape of the transversal strain wave has a very dispersive characteristic, and therefore a clear pulse cannot be distinguished from the response. The wave shape is caused by a frequency dependent wave speed that is slower at the low frequencies compared to the high frequency content.

The measured signal spectrums are presented in Figure 3(b). The spectrum of the longitudinal stress waves (top) has a harmonic distribution of the modal components. The transversal spectrum (middle) has an inharmonic distribution of the modal components that is caused by the dispersive wave propagation. The spectrum of the

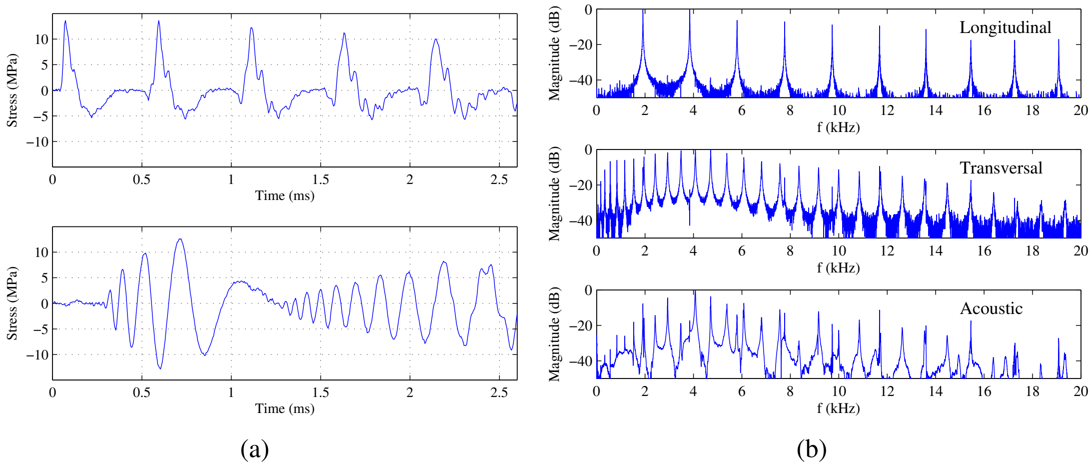


Figure 3: *Measured stress waves for steel bar exited with a longitudinal impact (a) Time-domain: longitudinal wave in the top plot and transversal wave in the bottom plot (b) Spectral-domain: longitudinal wave spectrum in the top plot, transversal wave spectrum in the middle plot and acoustic spectrum in the bottom plot.*

audio signal is a combination of the longitudinal and transversal modes. The spectral envelope of the audio signal has less energy at low frequencies ($f < 2$ kHz) than at higher frequencies. This is caused by the inefficient sound radiation of the steel bar at low frequencies.

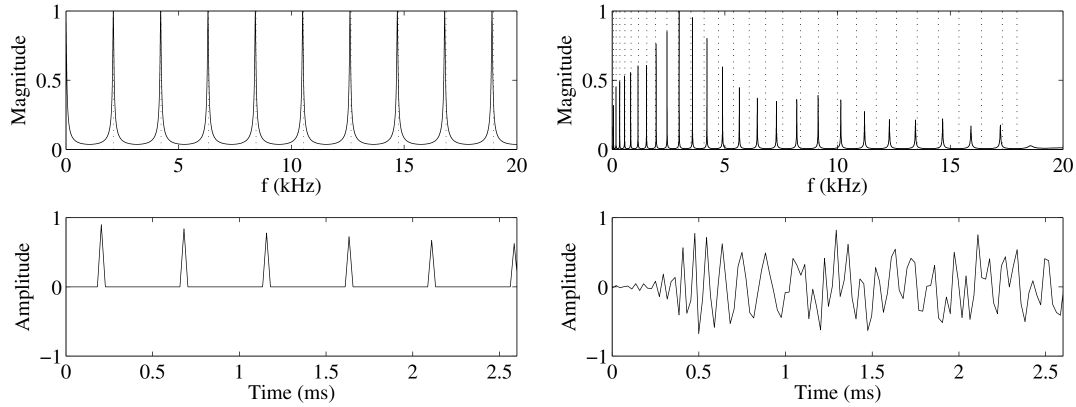
4 MODELING OF STRESS WAVES IN A STEEL BAR

The modeling approach is divided into two domains, longitudinal and transversal. The strain wave models are implemented using digital waveguides. The digital waveguides have been previously used in the musical instrument modeling [6, 7]. A digital waveguide is a comb filter that is used to create spectral peaks to desired frequencies. The longitudinal model is a feedback comb filter with an adjustable delay line and reflection coefficient. The delay line length is used to tune the model to match desired spectral peaks. The reflection coefficient is used to adjust the signal decay rate.

The transversal model has a similar structure as the longitudinal model. The only difference is the dispersion filter in the feedback loop that is used to model the dispersion by mimicking the frequency dependent wave speed. The dispersion filter can be realized with allpass filters that are used to realize the desired phase delay characteristics. Finally the model is completed by summing up the modeled longitudinal and transversal vibrations.

5 CONCLUSIONS

A vibroacoustic analysis and synthesis of a struck metal bar was investigated in this paper. First the basics of the struck steel bar vibration were presented. The strain waves and related audio signals of the struck steel bar were measured in anechoic



(a) (b)

Figure 4: *Model output and spectrum (a) longitudinal and (b) transversal.*

conditions. Based on the measurements and vibration theory a computational model was developed using modeling techniques that have been already applied in the field of musical instrument modeling.

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