PRECESSIONAL TRANSMISSION SOUND REASEARCH

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1. BASIC PARAMETERS OF SOUND

Sound measurement and analysis are required to determine what sound is typically generated and what sound is undesired noise. This analysis is accomplished by the use of a sound analyzer. A sound analyzer is an instrument which displays sound waves in the rms levels at various frequencies or frequency bands. Using an analyzer will help separate undesired frequencies from the sound spectrum and contribute to an accurate interpretation of sound data. The sounds generated during gear unit operation can be from one or more of the following major sources: gear dynamics; bearing dynamics; coupling noises; system resonance or critical speeds; accessories such as funs, lubrication systems, etc.

Sound may be defined as any pressure variation (in air, water or other medium) that the human ear can detect. Just like dominoes, a wave motion is set off when an element sets the nearest particle of air into motion. This motion gradually spreads to adjacent air particles further away from the source. Depending on the medium, sound propagates at different speeds. In air, sound propagates at a speed of approximately 340 m/s. In liquids and solids, the propagation velocity is greater – 1500 m/s in water and 5000 m/s in steel [8].

In the other hand sound is such a common part of everyday life that we rarely appreciate all of its functions. It provides enjoyable experiences such as listening to music or to the singing of birds. It enables spoken communication and it can alert or warm us – for example, with the ringing of a telephone, or a wailing siren. Sound also permits us to make quality evaluation and diagnoses – the chattering valves of a car, a squeaking wheel, or a heart murmur.

In many cases in our modern society, sound annoys us. Many sounds are unpleasant and unwanted – these are called **noise**. However, the level of annoyance depends not only on the quality of the sound, but also our attitude towards it. The sound of his new jet aircraft taking off may be music to the ears of the design engineer, but will be ear-splitting agony for the people living near the end of the runway. A creaking floor, a scratch on a record, or a dripping tap can be just as annoying as loud thunder.

Worst of all, sound can damage and destroy. A sonic boom can shatter windows and shake plaster of walls. But the most unfortunate case is when sound damage the delicate mechanism designed to receive it – the human ear.

The level of sound is normally described in terms of either sound pressure level at a given distance from the source or sound power level. In each of these, the desired quantity (pressure or power) is expressed in the numerator of a ratio with the reference level as the denominator. Because of the extremely wide range of levels measured (very small to extremely large) in everyday environments, both pressure and power ratios are expressed by logarithmic scale.

Sound pressure level, $\boldsymbol{L_p}$, expressed in decibels, is 20 times the logarithm to the base 10 of the ratio of the sound pressure being measured to the reference sound pressure [1,3]:

$$L_p = 20\log_{10}\frac{p}{p_0},\ [dB] \qquad (1)$$

where, p – is sound pressure being measured, μN/m^2, p_0 – is reference sound pressure 20 μN/m^2. The reference sound pressure, p_0, is internationally accepted as 20 microNewton/meter squared, which is about the threshold of normal hearing at a frequency of 1000 Hz. All sound measuring instruments respond to sound pressure.

Example: The sound pressure near a punch press is measured as being 0,0025 psi. What is the sound pressure 20 μN/m^2 in dB?

Since 1,0 psi = 6890 N/m^2, then 0,0025 psi = 17,225 N/m^2.

$$L_p = 20\log_{10}\left(\frac{17{,}22 N/m^2}{20\mu N/m^2}\right) = 118{,}7 dB$$

So we would commonly say the noise of the punch press is 119 dB.

The second main quantity used to describe a sound is the size or *amplitude* of the pressure fluctuations. The weakest sound a healthy human ear can detect has an amplitude of 20 millionths of a Pascal (20 μPa) – some 5000000000 times less than normal atmospheric pressure. A pressure change of 20 μPa is so small that it causes the eardrum to deflect a distance less than the diameter of a single hydrogen molecule. Amazingly, the ear can tolerate sound pressures more than million times higher. Thus, if we measured sound in Pa, we would end up with some quite large, unmanageable numbers. To avoid this, another scale is used – the *decibel* or dB scale.

2. GENERTION OF SOUND IN GEAR UNITS

The differentiation between sound and noise can be defined simply: sound is a variation in pressure; noise is undesired sound. Noise also implies undesired frequencies which tend to mask useful information, causing possible misrepresentation of actual sound characteristics. Examples of noises extraneous to gear sound measurement are lubrication pump noise, air-drill noise, instrumentation, electrical noise, etc.

Sound measurement and analysis are required to determine what sound is typically generated and what sound is undesired noise. This analysis is accomplished by the use of a sound analyzer. A sound analyzer is an instrument which displays sound waves in the rms levels at various frequencies or frequency bands. Using an analyzer will help separate undesired frequencies from the sound spectrum and contribute to an accurate interpretation of sound data. The bandwidth of the analyzer governs the amount of useful data displayed for analysis. The narrower the bandwidth, the more discrete frequency information available, the easier it becomes to identify extraneous noise frequencies from the other generated sound in a gear driven system.

In all possible cases, the elimination of unwanted noise in the area under investigation should be carried out before proper gear sound analysis is initiated. This will make the engineer's job of analyzing the data much easier and will enable him to give better results.

The sounds generated during gear unit operation can be from one or more of the following major sources:

- gear dynamics;
- bearing dynamics;
- coupling noises;
- system resonance or critical speeds;
- accessories such as funs, lubrication systems, etc [3,8].

Sound generation in gears is related to design tolerances and operation. The mating accuracy of a gear set must be maintained, commensurate with the desired operation. Gear sound is often generated by the mesh action of the teeth. If the teeth have irregularities in their profile or spacing, noise may be generated at the frequency of the irregularities. One must understand that a 100% accurate theoretical tooth profile will still generate sound due to the dynamics of gear mesh. Improper lubrication may allow noise to be generated in the mesh. The sounds generated will often be at the mesh frequency (i.e., the frequency or rotation times the number of teeth on the rotor), harmonics of mesh frequency, or at sideband frequency (mesh frequency plus and minus pinion or gear rotational frequency).

Sound in ball and roller bearings can be generated by the irregularities in the bearing elements, friction, deflections under load, misalignments, loose cages and races, windage, roller skewing and/or skidding, etc. Misalignments and deflections under load are the major causes of antifriction bearing noise.

System resonances and critical speed generate sound in gear units. The structural resonant frequencies of the casing and the baseplate can be excited by internally generated frequencies (tooth mesh) to produce noise. Care must be taken to determine the natural frequencies if support structures to ensure that the rotational frequency and other generated frequencies are not coincident to, or a multiple of, natural frequencies. Likewise, lateral and torsionale natural frequencies in the rotating system may be excited to produce noise if they are too close to a generated frequency or its harmonics.

Often, other equipment is required for proper operation of a gear unit. Accessories such as cooling fans and lubrication systems (pumps, motors, relief valves, etc.) can be sources of noise which may appear to be generated by the gear units.

Measurements of sounds provide definite quantities which describe and rate sounds. These measurements can provide benefits such as improved building acoustics and loudspeakers, thus increasing our enjoyment of music, both in the concert hall and at home.

Sound measurements also permit precise, scientific analysis of annoying sounds. However, we must remember that due to the physiological and psychological differences between individuals, the degree of annoyance cannot be scientifically measured for a given person. But the measurements do give us an objective means of comparing annoying sounds under different conditions.

Sound measurements also give a clear indication of when a sound may cause damage to hearing and permit corrective measures to be taken. The degree of hearing damage can be determined by *audiometry* which measures a person's hearing sensitivity. Thus, sound measurements are a vital part of hearing conservation programmes.

Finally, measurement and analysis of sound is a powerful diagnostic tool in noise reduction programmes – from airports, to factories, highways, homes, industrial areas and recording studios. It is a tool which can help to improve the quality of our lives.

All of these sources as well as extraneous noise from the surrounding environment (background noise) add up the overall sound level in the area of the gear unit. The interrelationship between them helps to define the sound level. The overall level is determined by the addition of different generated levels by the following expression [1,2]:

$$L_p = 10\log_{10}\sum_{i=1}^{N} 10^{(0,1 \cdot a_i)} \qquad (2)$$

where: L_p – is sound pressure level, dB; a_i – is sound pressure level from a single source or octave; N – is number of single levels investigated.

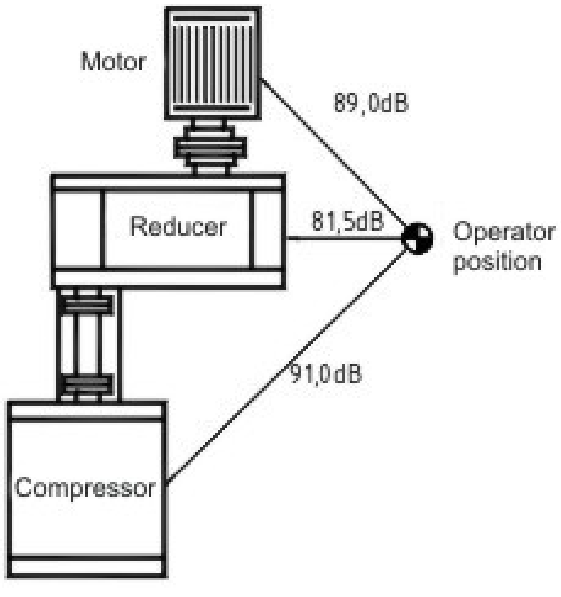


Figure 1. Calculation for expected sound level.

In an octave band analysis, N is the number of octaves.

Example 1: The installation in figure 1 shows a motor, reducer and a compressor in an industrial plant environment. The sound of each piece of equipment was measured by its manufacturer to have the listed sound levels at the operator location shown in figure 3. Totalling the levels by the formula (2) gives an expected level at the operator of 93,4 dBA.

$$L_p = 10\log_{10}\left[10^{8,9} + 10^{8,15} + 10^{9,1}\right] = 93,4\left[dB\ A\right].$$

Therefore, a means of adding or subtracting sound generated from different sources is also available. Any school student will tell you that (82+88=89) is an invalid equation. However, if we state that in the same environment 82 dB + 88 dB = 89 dB we would be correct.

3 EXPERIMENTAL MEASUREMENTS

3.1 Experimental stands

For experimental measurements we use experimental stand as shown in figure 2 with sound level meter Brüel & Kjær 2250 Light with following setup : **Diffuse-Field** for *Sound Field Correction*, **A** for *Frequency Weightings*, **Automatic** for *measurement Mode* and **10 minutes** for *Preset time*. The experimental stand is composed like is shown in figure 3 by: 1- electromotor; 2- precessional reducer; 3 – brake; 4 – rev-meter; 5 – sound level meter Brüel & Kjær Type 2250 Light.

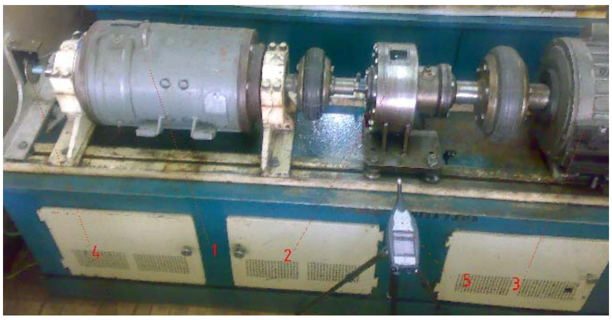


Figure 2. Experimental stand.

The 2250 Light has been developed specifically for measuring occupational, environmental and product noise, while complying fully with all the relevant national and international standards. Extensive user studies have been paired with state-of-the-art technology to make this analyzer a robust, effective and elegant tool for those applications.

3.2 Sound Level Meter 2250 light

Analyzer 2250 Light shown in figure 3 has been developed specifically for measuring occupational, environmental and product noise, while complying with all the relevant national and international standards.

Using the large, high contrast, touch screen interface, the analyzer can easily be set up to display and measure just what is needed from the extensive list of parameters provided by the analyzer.

Figure 3. Sound Level Meter Type 2250 Light.

2250 Light have installed Spund Level Meter Software, measuring all parameters simultaneously within its wide 120 dB dynamic range. For frequency analysis, the sonometer have installed 1/1 and 1/3 – octave software module.

Back in the office, USB connectivity lets us use the PC to archive, manage, view or even control 2250 Light, as well as export our results to software packages such as Microsoft® Excel and Bruel & Kjaer Types 7815, 7820 or 7825 for post-processing and reporting.

Uses and features of 2250 Light:

- environmental noise assessment, monitoring and complaints;
- occupational noise evaluation, selection of hearing protection;
- noise reduction, product quality control, general purpose Class 1 sound measurements;
- real-time analysis of sound 1/1 and 1/3 – octave bands;
- large, high-resolution touch-sensitive screen;
- plug-in rechargeable Li-ion battery;
- data storage on plug-in memory cards;
- 120 dB dynamic range – up to 140 dB;
- robust and environmentally protected (IP 44);
- upgrade to Type 2250 on exchange basis.

2250 Light combines renowned Bruel & Kjaer measurement excellence and the Type 2250 platforms ease of use, in an efficient and versatile sound measurement instrument. This analyzer was developed with special interest for the measurements of workplace noise. The comfortable and secure design feels in our hand. With the display located relatively close to us, the buttons fall precisely where they need to be for a one thumb operated Start, Stop and Save. The "*Trafic Light*" indicator surrounding the Start/Pause pushbutton gives us an immediate visual indication of measurement status – even in the brightest sunshine. The large, high contrast, touch screen/display, lets us select parameters on the display, and 2250 Light can memorise those setups for our next measurements [7,9].

As for occupational health noise parameters, nothing was left out. 2250 Light can measure Fast and Slow, A-weighted and C-weighted SPLs simultaneously, along with a separately weighted peak detector, so that the values we need to specify hearing protection are immediately on the display. Parallel analysis allows us to compare a 3 dB exchange rate average measurement with a selectable alternate 4,5 or 6 exchange rate, including separate dose, expected dose and exposure values.

2250 Light also offers three independent threshold peak event counters, along with simultaneous Fast, Slow and Impulse RMS detectors, to assess impulsive noise.

With the 1/1 octave frequency analysis software option, we are ready to instantly assess noise control and detailed hearing protection requirements for a surveyed location. With 2250 Light there is no filter switching, or range changing, all the octaves are measured at the same instant, along with the broadband A- and C-weighted values. For even more detail, add 1/3-octave frequency analyses option. Instantly see the maximum and average levels across 31 frequency bands spanning three decade from 12.5 Hz to 16 kHz [7].

2250 Light can be used as a hand-held device for easy portability, or it can be operated using our Windows® PC as an on-line USB controlled device in our laboratory. The user-defined templates make switching between applications easy [7].

But for more involved environmental applications, we will need to add the logging option. With this option we can set the instrument to record all, or up to ten selected measurement results at intervals from one second to one day, for a duration only limited by size of the CF or SD memory card used in the external memory slots. The display offers two simultaneous views, one of the complete profile and a "zoomed-in" 100-second "*window*", that are intuitively linked by the cursor.

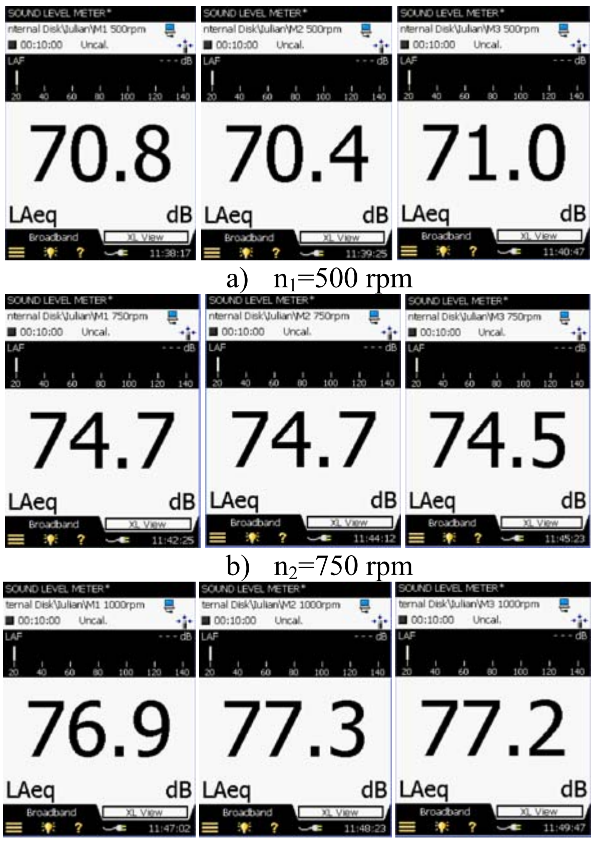
The wide 120 dB dynamic range of 2250 Light eliminates concern for overloads, and we can set a preset measurements time to add consistency to our measurements. Use the built-in headphone style (3.5 mm) output jack to send the signal out to other measurement instrumentation. The included utility program makes it easy to keep track of results in an organised, archive structure. And, of course, there is the Class 1 precision and reputation of Bruel & Kjaer, giving us and our customers complete confidence in our measurements, while adding value to our products.

For comprehensive data management and post-process reporting, consider using 2250 Light data together with Type 7815 Noise Explorer, which supports a wide range of user-definable graphic and tabular displays.

In all configurations, Type 2250 offers a variety of the same measurement. These views have no impact on the measurement, but they allow us what we want. [9].

3.3 Data calculating

The measured noise parameter is $\mathbf{L_{Aeq,T}}$, where the letter "**A**" denotes that the "A-weighting" has been included and **"eq"** indicates that an equivalent level has been calculated. Hence, L_{Aeq} is the A-weighting-equivalent continuous noise level, and **T=10 min** is preset time for measurement.



a) n_1=500 rpm

b) n_2=750 rpm

c) n_3=1000 rpm

Figure 4. *a)-three measurement for* $\mathbf{n_1=500\ min^{-1}}$ *b)-three measurement for* $\mathbf{n_2=750\ min^{-1}}$ *c)-three measurement for* $\mathbf{n_3=1000\ min^{-1}}$

In our case we made 3 different measurements for 3 different cases, when precessional reducer is minimum filled with lubricating cooling fluid. First case for revolution speed $\mathbf{n_1=500\ min^{-1}}$, second case for revolution speed $\mathbf{n_2=750\ min^{-1}}$ and third case for revolution speed $\mathbf{n_3=1000\ min^{-1}}$**.** For each case we obtained 3 different results like in figure 4.

3.4 Average noise level

If we have 3 different result and you need an average result you can use following formula:

$$L_{ptot} = 10\log_{10}\frac{1}{N}\sum 10^{0,1\cdot a_i} \qquad (3)$$

First case when n_1=500 min^{-1}

$$L_{ptot} = 10\log_{10}\frac{1}{3}\left(10^{7,08} + 10^{7,04} + 10^{7,10}\right) = 70,7\left[dB\right]$$

Second case when n_2=750 min^{-1}

$$L_{ptot} = 10\log_{10}\frac{1}{3}\left(10^{7,47} + 10^{7,47} + 10^{7,45}\right) = 74,6\left[dB\right]$$

Third case when n_3=1000 min^{-1}

$$L_{ptot} = 10\log_{10}\frac{1}{3}\left(10^{7,69} + 10^{7,73} + 10^{7,72}\right) = 77,1\left[dB\right]$$

4. CONCLUSIONS

Noise specification are written by governments, standards organizations, users, manufacturers and trade associations.

The most significant governmental noise specification has been the Occupational Safety and Health Act (OSHA) Regulations (US Standard – 29 CFR, Occupational noise exposure – 1926.52). OSHA placed limitations on the maximum sound level and exposure times to which an employee may be subjected at his working station without personal protective equipment. Protection against the effects of noise exposure shall be provided when the A-weighted sound pressure level exceeds those shown in table 1 [2].

See AGMA 914-B04, *Gear Sound Manual*: *Part II - Sources, Specifications and Levels of Gear Sound*, published by the American Gear Manufacturers Association, 500 Montgomery Street, Suite 350, Alexandria, Virginia 22314, http://www.agma.org.

When employers are subjected to sound levels exceeding those in table 1, feasible administrative or engineering controls shall be utilized. If such controls fail to reduce sound levels within the levels of the table, personal protective equipments shall be provided and used to reduce sound level within the levels of the table.

Table 1. Occupational noise exposure.

Duration per day, hours	**Sound Level dBA slow response**
8	90
6	92
4	95
3	97
2	100
1,5	102
1	105
0,5	110
0,25 or less	115

NOTE:
When the daily noise exposure is composed of two or more periods of noise exposure of different levels, their combined effects should be considered, rather than the individual effect of each. Exposure to different levels for various periods of time shall be computed according to the following formula:

$$F(e) = \frac{T(1)}{L(1)} + \frac{T(2)}{L(2)} + ... + \frac{T(n)}{L(n)}$$

$F(e)$ is equivalent noise exposure factor;
T is period of noise exposure at any essentially constant level;
L is duration of the permissible noise exposure at the constant level.

Example: A sample computation showing an application of the above formula is as follows. An employee is exposed at the levels for the following periods:
110 dBA for 0,25 hour
100 dBA for 0,5 hour
90 dBA for 2 hours

$$F(e) = \frac{0{,}25}{0{,}50} + \frac{0{,}5}{2} + \frac{2}{8} = 0{,}5 + 0{,}25 + 0{,}25 = 1{,}000$$

Since the value of $F(e)$ does not exceed unity, the exposure is within permissible limits.

If the variations in noice level involve maxima at intervals of 1 second, or more, it is to be considerate continuous.

In all cases where the sound levels exceed the values shown, a continuing, effective hearing conservation program shall be administrated.

In conclusion we can mentioned the fact that the results of researches have shown that the noise levels, emitted by the non-loaded reducer K-H-V considerably less norms regulated by the branch standard OST 2.N89-5-79 for planetary reducers and cylindrical double-reduction gears with appropriate capacity and OSHA Regulation (US Standard 29 CFR) shown in table 1 [2].

Future research steps will be focused on analyzing and researching the acoustic behaviour of precessional reducer filled to maximum oil capacity and comparison with the minimum oil level.

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