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Technical Article

Bearing Dynamics and Sound



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Bearing Dynamics and Sound

Preface

A growing awareness of noise pollution, prompted in part by government regulations, has been noticeable during recent years. One is hard-pressed to single out an industry that has not been affected, either as a user or a supplier.

In its role as a supplier, The Timken Company can look back on a long history–predating the current emphasis on noise abatement by many years–of actively practicing noise control. This philosophy is exemplified not only by an extensive sound test program in its production facilities but also by an ongoing commitment to research in both fundamental and practical aspects of bearing related sound.

It is very useful to picture the bearing as playing one of two very distinct roles. In one of these, its passive role as a transmitter, the bearing merely provides a path for energy transfer between the rotating and the stationary member, while in the second or active role, it causes its immediate environment to be excited by virtue of its rotation. It is important to recognize this distinction, particularly in situations calling for a diagnosis. Essentially, bearings play a significant role in the transmission of vibration in rotating equipment, however, they usually are not the predominant source of vibration.



NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
d_0	Inner raceway (mean) diameter	mm, in
D_0	Outer raceway (mean) diameter	mm, in
D_{W0}	Roller or ball (mean) diameter	mm, in
f	Excitation frequency	Hz
i	Harmonic index of carrier frequency, 0, 1, 2, 3, ..	
j	Harmonic index of modulating frequency, 0, 1, 2, 3, ..	
K_1, K_2, K_3	Geometry-related constants	
$K_{bearing}$	Bearing stiffness	N/m, lbf/in
$K_{housing}$	Housing stiffness	N/m, lbf/in
K_{system}	System stiffness	N/m, lbf/in
S	Rotational speed	rpm
Z	Number of rollers or balls per row	
α (alpha)	Contact Angle or ½ included cup angle (TRB only)	degree
β (beta)	½ included cone angle (TRB only)	degree
ν (nu)	½ included roller angle (TRB only)	degree

The bearing as a transmitter

Simply put, a bearing may be thought of as a massless spring/damper connecting a shaft to its housing. Typically, the interest lies in determining how vibration is transferred from housing to shaft or vice versa. For example, the excitation of meshing gears is carried along the shaft, through the bearing and to the exposed housing surface, where some of the energy is converted to airborne noise.

Tapered roller and angular contact ball bearings enjoy an advantage not found in other types of rolling element bearings. Since two bearings typically are adjusted against one another, the setting will govern the axial force. This influences the stiffness of the bearings and thereby the stiffness of the system. By merely varying the bearing setting, it may be possible to shift any unwelcome resonances out of the frequency range of interest. Maximum stiffnesses of approximately 1.75 x 109 N/m (10 x 106 lbf/in) are common in tapered roller bearings.

In manipulating the system stiffness, it is essential that the stiffness of the bearing supports (housing) be taken into account. In simple conceptual terms:

$$1/K_{system} = 1/K_{bearing} + 1/K_{housing}$$

While the prediction of stiffness in bearings is cumbersome at best, dealing with their damping characteristics is even more elusive. It has been demonstrated, however, that bearing setting will affect the amount of damping which can be realized.

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The bearing as an exciter



The excitation potential of any rolling element bearing is determined primarily by the topography of its rolling surfaces. For example, a severe force pulse would result if a gross imperfection, such as a spall of sufficient size, were present in an operating bearing. Similarly, small imperfections such as brinell marks, nicks and any other deviations from perfect roundness of the components, will cause smaller fluctuation in the dynamic force. Hertzian theory tells us that even minute deformations can result in forces of significant magnitude. Therefore, this is the mechanism causing the bearing to act as an exciter.

Surface irregularities of various origins lead to dynamic forces. These forces do not remain localized but are transmitted quite readily into the supporting structure.

The dependence upon a number of rather unwieldy variables prohibits the mathematical determination of the magnitude of these forces in any one bearing. Their frequencies can be determined very accurately, though, from the gross dimensions of the bearing and its operating speed. Three constants can be defined in terms of either the angles or the diameters of the bearing depending on the bearing type:

$$K_1 = \frac{\sin \alpha}{\sin \alpha + \sin \beta} = \frac{D_0}{D_0 + d_0}$$

$$K_2 = \frac{\sin \beta}{\sin \alpha} = \frac{d_0}{D_0}$$

$$K_3 = \frac{\sin \beta}{\sin \nu} = \frac{d_0}{Dw_0}$$

These constants, along with the operating speed (S), the number of rollers or balls (Z) and a harmonic index (i), permit the calculation of certain frequencies. They, in turn, identify specific disturbances (Table 1).

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Table 1
TYPE OF DISTURBANCE AND RESULTING EXCITATION FREQUENCIES

Disturbance	Frequency, Hz
Eccentricity of Rotating Member	$f_0 = S/60$
Out-of-Round of Rotating Member	$f_{1i} = i * f_0$
Roller or Ball Irregularity, e.g., nick or spall	$f_{2i} = 2 * k_1 * k3 * f_{1i}$
Inner Raceway Irregularity, e.g., nick or spall	$f_{3i} = Z * k_1 * f_{1i}$
Outer Raceway Irregularity, e.g., nick or spall	$f_{4i} = Z * k_1 * k_2 * f_{1i}$
Roller or Ball Size Variation (Rotating Inner Ring)	$f_{5i} = k_1 * k_2 * f_{1i}$
Roller or Ball Size Variation (Rotating Outer Ring)	$f_{6j} = k_1 * f_{1i}$

Measurement considerations

The frequencies listed in Table 1 are applicable whenever a bearing is evaluated. A typical approach employs an accelerometer attached on or near the bearing. By performing a narrow band frequency analysis of the acceleration signal, one can usually determine if the bearing is damaged or meets a user established vibration criterion.

To avoid ambiguity when identifying the acceleration spikes occurring at the above frequencies, the bandwidth must be sufficiently narrow. For example, as the operating speed decreases, so should the bandwidth.

It is not uncommon to observe modulation, particularly when the signal is obtained in a direction perpendicular to the axis of the bearing. Under these circumstances, the predominant evidence will be found at the frequencies f2i ± f5j or f2i ± f6j where i and j denote harmonic indices.

Up to this point it has been assumed that the bearing operates with a 360° load zone. If this is not the case, such as when operating with radial load and internal clearance or end play, the rolling elements moving in and out of the load zone cause a spectrum that tends to have a “smeared” appearance.

As one of the final steps in its quality assurance program, The Timken Company subjects its bearings to a vibration analysis in highly specialized, accelerometer-equipped test machines.

In addition, the following rationale is employed: “The vibration (dynamic force) level of a bearing, operating at a specific speed and under a specific preload, is compared to and must meet an established standard. If this is the case, then by implication the geometric imperfections are of such small magnitude that the bearing’s potential to act as an exciter is considered acceptable.” Note that this implies that the merit of the bearing is strictly a function of the geometric imperfections, not one of speed and/or load and/or the bearing supports. The vibration signature may, of course, differ under other combinations of speed and load.



Acoustic implications

The mechanical energy in the bearing-generated dynamic forces and those presented to the bearing from the rotating member for transmission to the stationary member, will first be transferred to the structure supporting the bearing. The energy then permeates the structure and will be partially converted to acoustic energy upon arriving at an air/solid interface. Depending upon the mass, stiffness, geometry and boundary crossings characterizing the structure, the mechanical energy will undergo modifications. As a result of this transfer function, the prevailing acoustic energy (or airborne sound) will be a function not only of the mechanical vibration of the bearing but also the attenuation/amplification characteristics of each particular structure.

One such structure is the quality assurance equipment employed by The Timken Company. Bearings are tested for vibration in a relatively unenclosed configuration, i.e., one in which a large percentage of the bearing surface is exposed. Clearly, this condition is acoustically quite different from one in which the bearing is fully enclosed, as for example, in a machine tool.

The structure greatly influences the outcome of an acoustic measurement. Since sound is mainly caused by transverse vibration of the housing walls, a stiffer housing tends to be less noisy than one that is less rigid. Thus, any comparisons made or conclusions drawn between dissimilar structures are at best haphazard. The design of the structure can profoundly affect the overall noise characteristics of the system. This is the most important reason for not attaching sound level specifications, dB(A), to bearings.

Design considerations

Usually, resonances can be shifted or minimized by selective design, i.e., the shrewd manipulation of mass and/or stiffness. Where possible, impedance mismatches should be part of the design. For example, the vibration path between some electric motors and their bases is interrupted by rubber-like inserts. Also, consideration should be given to damping, either in the form of visco-elastic layers or mechanical discontinuities. The latter is realized wherever bolts, rivets or interference fits occur.

Within this context, the excitation potential of the bearing can be optimized by a variety of different techniques. An increase in the operating speed of a bearing causes an upward shift toward the frequency range of maximum hearing sensitivity. Simultaneously, the overall vibration level increases. A variation in preload/end play of the bearing can be utilized to bring about a “most favorable” condition. Run-in will typically result in some “quieting”. The same effect can be observed by going from a condition of marginal lubrication to one of “adequate” lubrication, but there is a point where additional lubricant flow no longer produces a benefit. It is good practice to fully enclose the bearing to minimize the direct acoustic path.

Assistance is readily available from The Timken Company engineers. Their experience can assist the user in selecting the proper bearing.

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The Timken team applies their know-how to improve the reliability and performance of machinery in diverse markets worldwide. The company designs, makes and markets bearings, gear drives, automated lubrication systems, belts, brakes, clutches, chain, couplings, linear motion products and related industrial motion rebuild and repair services.

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