기어박스의 기어와인소음연구

Investigation on Gear Whine with Virtual Designed Gearbox

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1. Introduction

In automotive application, gear whine is a main unpleasant noise which is noticeable to passengers even at relatively low levels. It is widely recognized that the characteristic gear whine is generated by a constant harmonic displacement excitation, caused by errors in the actual tooth position with its perfect tooth position, which is called Transmission Error (TE). [1] The vibrations excited by the TE are transmitted through the gears, bearing under gears and shafts to the main bearings where they are coupled to the housing and produce acoustic radiation.

Much effort has been made to reduce TE, hence decrease gear whine. However, TE has complex causes such as manufacturing and assembly imperfection and elastic deflection of shafts, bearing and gear tooth itself, and housing deformation. Moreover, gear whine is a tightly system dependent noise which means a slight change in any parts of gearbox may lead to different system resonant frequency. Therefore, system-level investigation is necessary to guarantee the accuracy and reliability of design.

Bearing act as a spring with mass in transmitting vibration and its stiffness directly affect vibration level from internal shaft to the housing which will finally radiate as a noise. [2,3]Nonlinear stiffness of bearing may be decided by macro and micro geometry, applied load, assembly conditions, etc. This paper will simulate the bearing preload effect on system response of specified TE excitation with one virtual-designed 5-speed manual transmission gearbox.

2. Modeling and Analysis Approach

Complete numerical model of 5-speed manual transmission gearbox was built in commercial software RomaxDesigner. [4] All gears/shafts/bearings/clutches are modeled with actual dimension. Exact duty cycle is applied based on test requirement. Bearing model includes the non-linear effects of internal clearance, and preload on bearing stiffness. (See Fig.1) Housing and differential case are imported FE model which using node connected with RxD model. (See Fig.2)

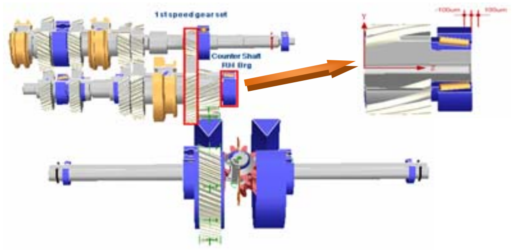


Fig. 1 Gearbox model and housing

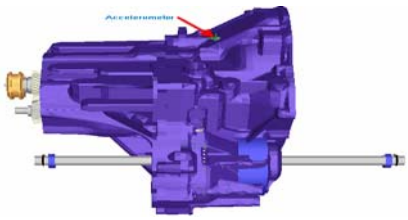


Fig. 2 Application preload

In order to simulate the bearing preload effect on system vibration characteristic, counter shaft right bearing was chosen and TE excitation from 1st speed gear sets was considered. (See Fig.1) One accelerometer was condensed on housing to collect vibration data which can be validated by product test. (See Fig.1)

Two reverse direction preloads were applied on outer race of taper roller bearing. (See Fig.2) .In practice preload is used to compensate internal clearance and enhance bearing life. Therefore, preloads are normally negative. (We define preload increase internal clearance as positive) Here positive preload is to simulate the shaft floating which is caused by manufacturing and assembly process.

Analysis process refers to Fig.3.

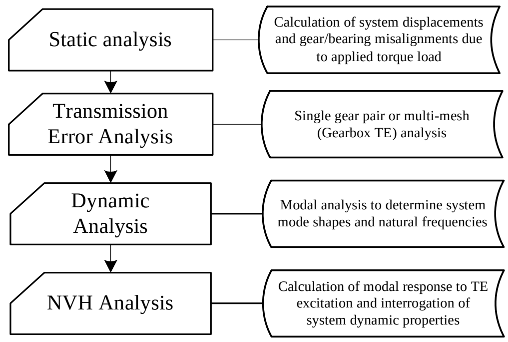


Fig.3 Analysis flow chart

3. Analysis Results and Discussion

Bearing Stiffness: Based on static analysis, bearing stiffness under different preload conditions was calculated. See table.1. It shows that positive preload obviously decrease the bearing stiffness comparing with increase by negative preload. This is mainly because ideally designed bearing has zero internal clearance.

Table1. Bearing stiffness for three different preloads

Preload (um)	X (N/mm)	Y (N/mm)	Z (N/mm)	XX (Nmm/rad)	YY (Nmm/rad)
-200	2.28E+06	2.28E+06	1.69E+05	5.37E+07	5.37E+07
0	2.09E+06	2.10E+06	1.56E+05	4.85E+07	4.77E+07
200	7.06E+05	4.89E+05	4.45E+04	1.08E+07	1.75E+07

Transmission error: Under 1st load case, static transmission error and corresponding harmonic (using FFT) on 1st speed gear set was calculated by gear micro-geometry analysis. Fig.4 and Fig.5 indicate highest displacement in line of action (LOA) is about 17.29um and three preload cases only have slight difference in 2nd and 3rd harmonic. This means effect of preload is inconspicuous in static stage.

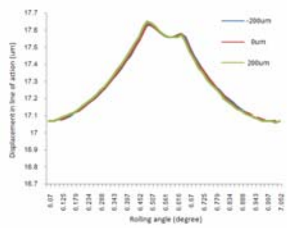


Fig.4 Transmission Error

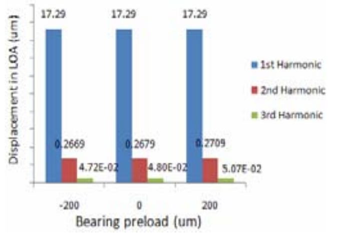


Fig.5 First three harmonics

Dynamic Transmission Error: it is the actual displacement between the two gears pair mesh nodes, which is defined as:

$$TE_{dynamic} = D_T + TE_{static}$$

$$D_T = \psi \left[\frac{1}{[K](1-r^2+2icr)} - \frac{1}{[K]} \right] \psi [F]_g$$

Frequency has high level of dynamic TE imply the likelihood for whole gearbox to be excited is high. Easy to see that positive preload has different dynamic TE from 550Hz to 1200Hz. This imply that response feature was changed.

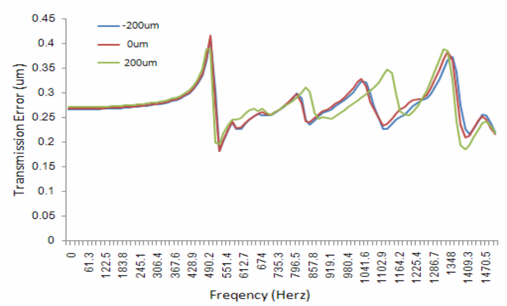


Fig.6 Dynamic Transmission Error

Component modal shape: For all three preload cases, first critical frequency is about 510Hz which also has highest modal flexibility. Fig.7 shows the modal shape of counter shaft at 510Hz. All support nodes and x, y, z deflection are displayed. It can be observed that deflection in positive preload case on right bearing node is higher than others. It will lead to higher vibration on housing consequently.

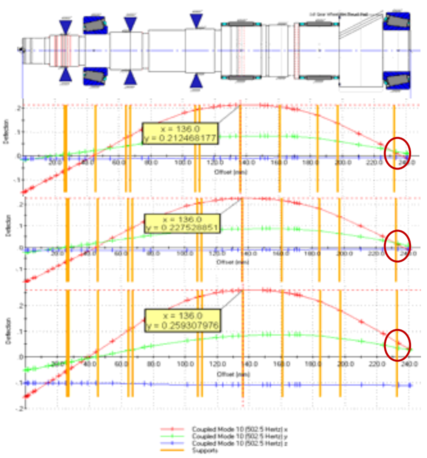


Fig.7 Counter shaft modal shape at 510Hz (-200,0,200)

Housing vibration: Vibration is transmitted through bearing to housing. Fig.8 shows the acceleration on test point. Obviously, positive preload case has higher value from 1100Hz to 1300Hz. The rest two case have almost same result.

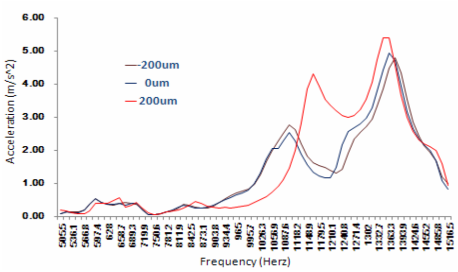


Fig. 8 Acceleration

Waterfall in Fig.9 shows the displacement at test point along with the input shaft speed from 0 to 8000rpm. Same result can be found that positive preload case has quite high displacement around 2000rpm, however the remainders have no big difference. First three harmonics have been included.

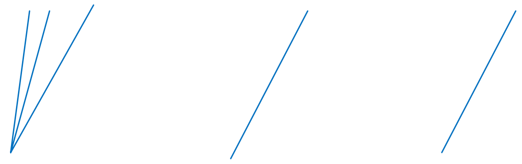
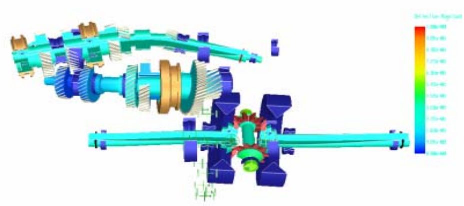


Fig. 9 Displacement waterfall (-200,0,200)

System model shape: whole system modal shape for first two critical frequencies around 510Hz and 1170Hz were shown in Fig.10. This will help to examine the main contribute of certain frequency resonance. (As no big difference between three cases, only deflection for zero preload case)


a) 510Hz

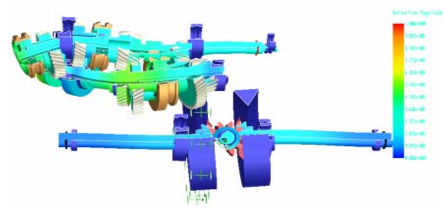

b) 1170Hz

Fig. 10 System modal shape

4. Conclusion

Effect of bearing preload on vibration has been investigated in one completely developed virtual model. Result shows:

Bearing preload change lead to bearing stiffness difference, consequently affect system response of TE excitation and vibration transmitting performance. Furthermore, in particular in this gearbox, applying positive preload (equal to increase internal clearance) was found more likely cause resonance in comparative lower frequency range owing to bearing stiffness decrease. This will be helpful for better understand and control the gear whine from system level.

Acknowledgement

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