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Analysis of Crankshafts Vibrations to Compare the Dynamic Behavior of Steel and Cast Iron Crankshafts

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Abstract: Due to the requirements of advanced industries to use lighter materials at high speed, static analysis of stress and strain can not be applied as a complete and powerful method, the dynamic behavior of the system should also be considered, however, the results should be confirmed by experiment. In this research, first, in order to investigate the effects of flywheel on natural frequency of crankshaft, the crankshaft, by using ANSYS software, was modeled in two cases; with flywheel and without flywheel at free-free condition. In the second phase, experimental modal analysis; the way that gives particularization of system responses, was applied to measure Frequency Response Function FRF). To do the experiments, the crankshaft was hanged in the laboratory and impact testing was applied to obtain FRF by a two channels FFT analyzer. Since the FRF is independent from input forces and actually it shows the inherent characteristics of the structure at the measuring points, FRF was measured just at drive points for each crankshaft. Finally, based on theoretical and experimental results, it is concluded that the cast-iron crankshaft is better to be used in NISSAN-2400 engines than steel crankshafts.

Key words: Crankshaft, Vibration, dynamic behavior, modal analysis, frequency response function, NISSAN 2400cc

INTRODUCTION

Up to now, most of crankshafts have been made by steel that are forged or casted, however, the number of crankshafts that made by Cast-Iron are less. Crankshaft made by Sphero Cast-Iron, has higher modulus of elasticity than the regular Cast-Iron one and trend in automotive crankshaft design is to replace Sphero Cast-Iron with forged steel due to its less cost. Moreover, a research showed that Sphero Cast-Iron is better for crankshafts with bigger pin diameter[1]. Generally, unbalancing in reciprocating device is not an only reason of producing noise and sound in an engine in small period of its speed, since the engines are usually designated so that the inertia forces are balanced completely. With refer to the researches, the source of engine sound and noise is mainly due to torsional vibration of crankshaft, which is intensified due to combustion pressure and inertia forces[1].

The present study was undertaken in light of this background to investigate the theoretical and experimental vibration of steel and Cast-Iron crankshaft in order to compare them[2]. Ishihama[3] showed that the crankshaft vibrates at resonance frequency, when the second harmonic of the engine rotational speed coincides with its natural torsional vibration frequency. Then he concluded that the tuning of the torsional vibration resonant frequency of the crankshaft could be done by varying the polar moment of inertia of the crankshaft, is an effective way to reduce engine vibration.

In the early 1990s, Sumitomo Metal industries[1] presented some information in order to compare the NVH performance of forged steel crankshafts with cast ductile iron crankshafts, however, in their study, the torsional vibration of crankshafts was not discussed. Moreover, Ishihama *et al.*[4] built a simple composite mathematical model capable of simulating the crankshaft-power plant shell-coupled structure using measured oil film stiffness as the connecting element. The results confirmed that the natural frequency coincidence of the crankshaft and the power plant shell structure, should be avoided[4].

MATERIALS AND METHODS

In order to investigate the dynamic behavior of the crankshaft, the following steps were followed[2]:

First, ANSYS software was used for theoretical analysis of the problem. Then the crankshaft was modeled and investigated in two cases; by flywheel and without flywheel and in free-free condition in order to obtain the effects of flywheel on the natural frequency of crankshaft.

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In the second phase, modal analysis; the way that gives us particularization of system responses was applied for computing Frequency Response Function (FRF) measurements. Since the aim of this research was to investigate just the torsional vibration of the crankshafts and not their bending vibration, the boundary conditions in the engine were not applicable in this investigation. In the next stage, the experiments were performed in which the crankshaft was hanged in the laboratory and impact testing procedure was applied to obtain FRF. Two channel FFT analyzer was used to compute FRF. Since FRF is independent from input forces and actually it shows the inherent characteristics of the structure at the measuring points, FRF is measured just at drive points for each crankshaft.

EXPERIMENTAL MODAL ANALYSIS

Experimental modal analysis is the process of experimental determination of modal parameters such as frequency, damping factors and modal vectors of a linear, time-invariant system[5]. The modal parameters can be determined by analytical methods such as finite element analysis. A common reason for using experimental modal analysis is to verify the result of the analytical approach. However, often, the analytical model does not exist and the modal parameters are determined experimentally. Moreover, experimental modal analysis is used to explain a dynamics problem (vibration or acoustic) whose solution is not obvious from intuition, analytical models, or previous experience[3].

Experimental modal analysis began in the 1940s with work oriented toward measuring the modal parameters of an aircraft so that the problem of flutter could be accurately predicted. At that time, the transducers measured dynamic forces were primitive and the analogue nature of the approach yielded a time-consuming process that was not practical for most situations.

With the invention of digital minicomputers and the Fast Fourier Transform (FFT) in 1960s, the modern era of experimental modal analysis was initiated. Today, experimental modal analysis presents an interdisciplinary field that makes use of aspects of signal processing, mechanics, vibration, acoustics, control theory and applied mathematics.

RESULTS AND DISCUSSION

Due to the investigation done by Ishihama, torsional vibration is the main reason of engine noise in small period of engine speed[1], therefore, just the torsional vibration was considered in this research. At first, the crankshaft was modeled as shown in Fig. 1 and then by using modal analysis of ANSYS software, considering free-free condition, the natural frequency and mode shapes were found. In this model, the element of solid 45, which is three dimensional and has 8 nodes was used. The results showed that the first 6 modes are rigid modes with frequency equal to zero. The other natural frequencies from 7 up to 15 are listed in Table 1. Natural mode shapes were calculated and the results showed that the crankshaft has torsionl vibration in 11th and 14th modes as shown in Fig. 2. Figure 3 shows the deformation of crankshaft in 9th mode. In the second phase, FRF was computed for both crankshafts as shown in Fig. 4 and 5.

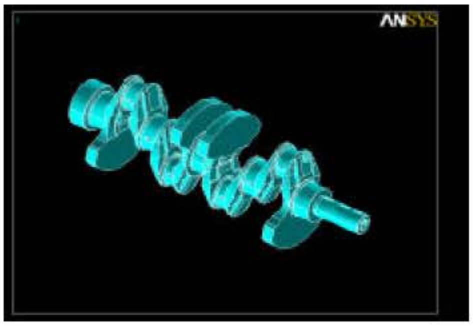
Fig. 1: Crankshaft ANSYS model

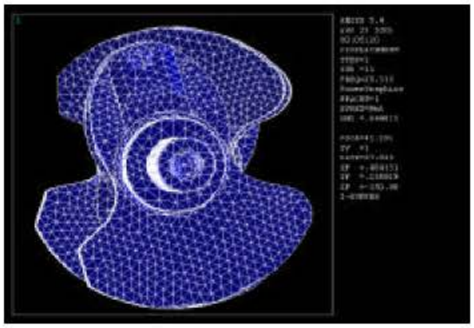
Fig. 2: Deformation of crankshaft in 11th mode

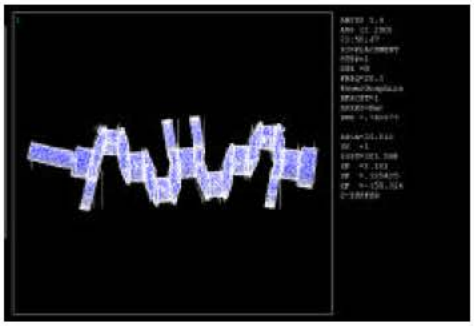
Fig. 3: Deformation of crankshaft in 9th mode

Table 1: Natural frequency of crankshafts (without flywheel) from 7th up to 15th mode

F 15 (Hz)	F 14 (Hz)	F 13 (Hz)	F 12 (Hz)	F 11 (Hz)	F 10 (Hz)	F 9 (Hz)	F 8 (Hz)	F7 (Hz)	Natural frequency
1587	1215	1091	905.3	829.5	688.3	655.6	399.4	286.9	Crankshaft steel
1529	1170	1050	866.3	798.8	650.3	632.3	384.6	276.2	Crankshaft Cast iron

Table 2: Natural frequency of crankshafts with flywheel from 7th up to 15th mode

F 15 (Hz)	F 14 (Hz)	F 13 (Hz)	F 12 (Hz)	F 11 (Hz)	F 10 (Hz)	F 9 (Hz)	F 8 (Hz)	F7 (Hz)	Natural frequency
1122.4	1022.0	817.9	545.2	540.9	457.3	385.2	226.4	174.2	Crankshaft steel
1103.5	1004.7	804.1	536.0	531.7	449.6	378.7	222.6	171.3	Crankshaft Cast iron

Table 3: Error between the result of software and modal analysis

Cast iron crankshaft	Steel crankshaft	
2.29%	3.94%	First natural frequency
1.21%	4.00%	Second natural frequency

Table 4: Resonance frequency and number of harmony for steel crankshaft

Engine (rpm)	Resonance frequency(Hz)	Number of harmony
2250	450	12
2700	450	10

Table 5: Resonance frequency and number of harmony for steel crankshaft

Engine (rpm)	Resonance frequency (Hz)	Number of harmony
2290	458	12
2748	458	10

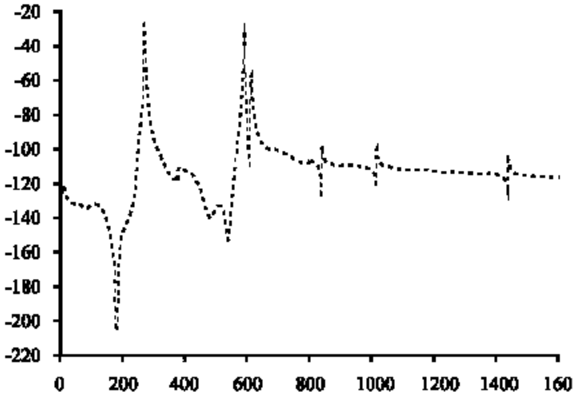

Fig. 4: FRF measured for cast iron crankshaft

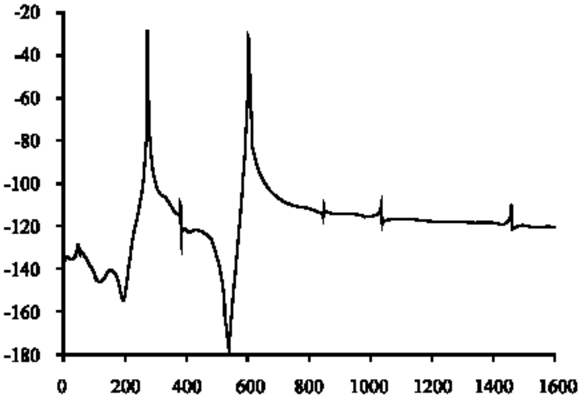

Fig. 5: FRF that measured for steel crankshaft

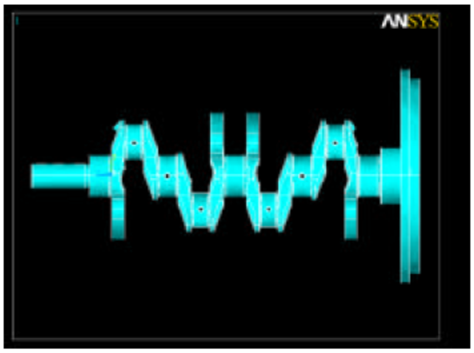

Fig. 6: Crankshaft ANSYS model with flywheel

With comparing the results from the first phase and the second phase, it is understood that the results are very close and the model generated in ANSYS software is good. Considering this matter that the flywheel is connected to crankshaft and knowing that the model is satisfactory, the flywheel was added to the crankshafts in software model (Fig. 6) in order to find the natural frequencies in this situation and as a result obtain the effects of flywheel on natural frequency of crankshaft. The results are shown in Table 2. With respect to these values, the effect of flywheel on vibration could be shown. In this situation, cast-iron and steel crankshafts have torsional vibration in 449.8 and 457.3 Hz, respectively.

Crankshaft can be vibrated at various orientations; however, the important mode is the first mode, i.e. when one node is located between flywheel and nearest crank. In the second mode, there are two nodes and both sides of crankshafts are moved in the same direction and the middle section shifts in adverse direction. Because in this mode, the length of shaft which is twisted in one direction, is shorter in comparison to the first mode, therefore, in the second mode the strength of the shaft is more and thus the first mode should be considered in this investigation.

The difference between the results of software and modal analysis are shown in Table 3 and with respect to close results, this model can be used in another vibration analysis like the actual one. If frequency of any harmonic component of torque is equal (or close) to the frequency of the first mode of vibration, a condition of resonance should be occurred and the machine is said to be running at a critical speed. The number of complete oscillation of the elastic system per unit revolution of the shaft is called the order of critical speed. An order of a critical speed that correspond to an harmonic component of torque from the engine as a whole is called a major order. A critical speed also can be found, corresponds to the harmonic component of the torque curve of a single cylinder.

A four-cylinder four-cycle engine has two equally spaced firing impulses per revolution. The major modes of 2, 4, 6, 8, 10, 12, etc., are obtained from a phase diagram that considers the engine force balance at frequencies of 2, 4, 6, 8, 10, 12, etc., times rotation speed. The critical speeds occur at ($60\ f_n/q$) rpm where f_n is the natural frequency of the modes (Hz) and q is the mode number of the critical speed[2]. The critical speed of both crankshafts are calculated and shown in Table 4 and 5. As shown in these tables, resonance in cast iron crankshaft occurs in lower rpm and with respect to the rated rpm of Nissan engine (2760 rpm), it is concluded that cast iron crankshaft in this engine has torsional frequency that is too far to rated engine rpm and therefore, it is better to use this type of crankshaft in this engine.

CONCLUSIONS

The calculated results from software agree with the modal analysis (experimental results), so it is possible to use this model in any other vibration analysis and do more investigation. Moreover, it is concluded that the cast iron crankshaft is better for using in NISSAN-2400 motors in compare to the steel crankshaft.

ACKNOWLEDGEMENT

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