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INVESTIGATION OF TORQUE-FLUCTUATION REDUCER MADE OF PERMANENT-MAGNETS FOR SCREW COMPRESSORS

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ABSTRACT

We developed a torque-fluctuation reducer, which can almost completely cancel a screw compressor's torque-fluctuation and reduce its vibration and noise. The device consists of inside and outside rings. Each ring has eight pairs of permanent-magnets arranged in a circle—one S- and - N pole pair for each of the male rotor's lobes. The inside ring is fixed to the male rotor shaft, and outside ring is fixed to the casing. Turning the inside ring, produces magnetic forces, which in turn cause sinusoidal torque fluctuations. We tuned the reducer for a 7.5 kW oil-injected air compressor. The male rotor's rotational vibration was reduced less than 10% of its original. The sound noise level at the tooth-contact frequency decreased to 5dB at 1 m from the front of the compressor package.

INTRODUCTION

Torque fluctuation is a characteristic source of vibrations that cause structure-born noise in screw compressors. This fluctuation is caused by the gas pressure that is applied to the lobes due to the compressing action, and by the transmission error between the rotors. With our particular compressors, rotor profiles are so accurate that transmission error is too insignificant to contribute to torque fluctuation.

We have confirmed that torque fluctuation causes rotational vibration in the screw rotors, as well as counter-vibration in reaction to this in the casing. The rotational vibration's major element falls of the tooth-contact frequency, and its amplitude and phase remain steady in for a fixed set of compressor conditions.
STRUCTURE & MECHANISM

Our torque-fluctuation canceller was fixed to the end of a oil-injected air compressor (Fig. 1). The canceller consists of inside and outside rings, each of which has eight pairs of permanent-magnet blocks arranged in a circle— one pair for each of the male rotor's four lobes. The orientations of neighboring magnet blocks alternate from S-pole to N-pole. The inside ring is fixed to the male rotor shaft, and the outside ring is fixed to the casing. There is a circular air gap between the two rings.

Turning the inside ring generates magnetic forces which, in turn, generate sinusoidal torque fluctuation (Fig. 2) without any axial or radial forces. Using a load cell which we designed ourselves, we confirmed the torque pattern was approximately the same as a sine curve. For example, the curved line in Fig. 2 shows the values measured from our #4 magnet set. The principle is same as that used in magnetic couplings. If the generated torque fluctuation equals the compressor's original torque fluctuation in frequency and amplitude, and the phases are opposite, the fluctuation should be canceled.

METHOD OF TESTING

We built and tuned the canceller for a 7.5 kW oil-injected air compressor. The parameters that need to be matched are amplitude and phase. Frequency does not need to be matched, because the canceller automatically generates the same frequency of torque fluctuation as the screw compressor, due to the matching number and spacing of the magnet blocks. The amplitude of torque generated can be tuned via the air gap thickness. We prepared cancellers with 6 different air-gap width, and labeled them #1 ~ #6 (Table 1).

Phase can be adjusted by changing the angle at which the outside ring is fixed to the casing. A reference angle for the phase is the delivery starting angle of the male rotor, at the stable neutral angle (Fig. 2 (c)) of the torque-fluctuation reducer.

The measuring instruments and test system are shown in Fig. 3. The “Air Block” is the screw compressor body including the casing, rotors, and torque fluctuation reducer. It stands on a pedestal and is driven by motor via rubber belts. The entire apparatus is set on a base and covered by a package which serves as soundproofing.

We evaluated the reducer for rotational fluctuation of the male rotor, and for vibration acceleration of the casing. To do this, we therefore attached sensors to the male rotor and
casing. An acceleration-pickup (accelerometer) was attached with a stud-bolt to a foot of the casing. A couple of magnet pickups and a pulse generating gear generated pulses, in proportion to the rotor's rotation speed. The rotational fluctuation can be determined using a phase-shift detector, which compares the rotating pulse against a mean pulse generated by a mean-pulse generator, which calculates the number of rotating pulses in a given unit of time. We evaluated the effect of the reducer on vibration acceleration of the base, and on the sound level at 1 m from the front of the package. We analyzed the measured outputs with a FFT-analyzer.

**PHASE ADJUSTMENT**

The vibration spectra of the casing is shown in Fig. 4 for various phases of added torque fluctuation. The reducer only effects the vibration of the tooth-contact frequency. Other vibration frequencies are steady, and seem to be independent of the tooth-contact frequency.

Focusing more detailed attention on the tooth-contact frequency, the amplitude tendencies with respect to phase are shown in Figs. 5 and 6. Figure 5 graphs the effect on casing vibration, and Fig. 6 that on the rotational vibration. The additional parameter is the width of air gap between the magnet pairs (#1~#6).

Both of these graphs show that the best phase match is at 45 deg., because that is the position with the minimum amplitude remaining after canceling. This remaining amplitude varies similarly with the amplitude remaining of the two perfectly out-of-phase sine curves (Fig. 7). This means that the effect of our torque-fluctuation reducer can be explained as the summation of original and additional canceling torque fluctuations modeled as two sine curves.

**AMPLITUDE ADJUSTMENT**

At the best phase-cancellation angle (45 deg.), the remain amplitudes have a linear relationship to change in the torque amplitude of the canceller (Fig. 8). If we look at all measured values, including the original vibration (i.e. that in which the canceller's torque is 0), the addition of torque amplitude can be seen to change the remaining (i.e. post-cancellation) amplitudes of the casing vibration and of the male-rotor vibration. Each amplitude takes the shape of a bent line with single reflection, at the minimum vibration
point. The casing and rotor vibrations become minimized at the different points. We think the reason for this difference is related to inertia due to the presence of the female rotor.

We think the best matching condition for practical use is the one at which the casing vibration is minimized, because casing vibration spreads more easily than that of the male rotor. The amplitude of the additional cancellation torque for this condition is 2.2 N⋅m, which is 7% of the compressor's input torque of 30 N⋅m.

EFFECTS ON VIBRATION & NOISE REDUCTION

At these best-match conditions for phase and amplitude, the torque-fluctuation reducer works as follows.

The vibration-reduction results at the center of the base are shown in Fig. 9. Naturally, the element at the tooth-contact frequency has been reduced; and the elements at the rotational and electro-magnetic frequencies of the motor have been greatly reduced much, as well. The latter fact may be a sign of the influence of the compressor's torque fluctuations on the motor vibration.

The noise-reduction result as measured at a point 1 m from the front of the compressor package is shown in Fig. 10. The noise element at the tooth-contact frequency has been reduced by 5.1 dB. Unfortunately, the overall noise level has not been reduced to the same extent as vibration, because the 301 Hz air-suction noise has become louder than the other frequency elements. Of course, this air-suction noise can be reduced by using a silencer.

CONCLUSIONS

With the best match between the compressor and the torque fluctuation canceller, the male rotor's rotational vibration decreases to less than 10% of its original value. The sound noise level at the tooth-contact frequency decreases by 5.1 dB at a point 1 m from the front of the compressor package. Under this best-match conditions, the amplitude is 7% of the power-input torque, and the phase is 45 deg. off from the discharge starting angle of the male rotor.
Fig. 1 Torque Fluctuation Reducer installed in Screw Compressor [unit : mm]

<table>
<thead>
<tr>
<th>No.</th>
<th>Air Gap [mm]</th>
<th>Maximum Torque[Nm]</th>
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<tbody>
<tr>
<td>#1</td>
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<td>6.6</td>
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<td>#2</td>
<td>2.0</td>
<td>5.4</td>
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<td>#5</td>
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<td>2.9</td>
</tr>
<tr>
<td>#6</td>
<td>6.0</td>
<td>2.5</td>
</tr>
</tbody>
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Fig. 3 Measuring Instruments and Test System

Fig. 4 Effect of Torque-Fluctuation Reducer
Fig. 5 Effect of Torque Fluctuation Reducer on male rotor’s rotational vibration

Fig. 6 Effect of Torque Fluctuation Reducer on casing-vibration acceleration

Fig. 7 Remaining Amplitude for Sum of Two Sine Curves

Fig. 8 Remaining Amplitude and Best Matches

Fig. 9 Vibration-Reduction Results

Fig. 10 Noise-Reduction Results