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TEST RESULTS OF A NEW DAMPER SEAL FOR VIBRATION REDUCTION IN TURBOMACHINERY

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ABSTRACT

A new type of labyrinth gas seal for damping vibration and whirl, called the TAMSEAL, has been evaluated in both non-rotating and rotating tests at Texas A&M University. Test results of the prototype, along with comparison tests of a conventional labyrinth seal, show up to one hundred times more direct damping than the conventional bladed seal. The new design also has a feature that blocks swirl of the working fluid, which is known to be rotordynamically destabilizing in machines with conventional seals. Coastdown tests of the new seal were conducted at various pressures on a rotordynamic test apparatus with a critical speed at 4000 rpm and compared with identical testing of a conventional labyrinth seal. Rap tests of both seals were also conducted to measure the logarithmic decrement of free vibration, and the leakage of both seals was measured. Test results show large reductions in peak vibration at the critical speed in all cases, with the critical speed being completely eliminated by the TAMSEAL at some pressure drop conditions. The leakage rate of the tested TAMSEAL is higher than the conventional seal at the same clearance, but the large reductions in vibration and whirl amplitudes suggest that the TAMSEAL could be operated with smaller clearances than conventional labyrinth seals.

DESCRIPTION OF THE TAMSEAL AND TEST RIG

The most common type of pressure seal in turbomachinery is the labyrinth seal. A labyrinth seal consists of a series of circular blades and annular grooves that present a tortuous path for leakage of the working fluid. The TAMSEAL is a revolutionary development of the teeth on stator labyrinth seal. There are two distinct features of the TAMSEAL that work together to produce high damping. The first distinct feature is the radial rotor to blade clearance that increases along the axial flow path of the gas. The second distinct feature is placement of segregating partitions in the annular grooves of the seal. The combination of these two features is unique and has never been incorporated in any other seal design. A computer code predicts that the optimal blade number for damping is 2, increasing blade number will decrease both leakage and damping. Figure 1 is a cross-section drawing of a two-bladed configuration with four circumferential pockets.

Test results from a nonrotating apparatus were reported in 1993 (Vance and Schultz). This paper reports rotating tests. Figure 2 is a cross-sectional sketch of the rotordynamic test apparatus. The seal journal is attached to the end of the shaft. The journal is enclosed inside a sealed housing. Actually there are two identical TAMSEALs installed back-to-back around the overhung journal disk. Pressured air is supplied to a plenum chamber between the two seals. There are two leakage flows going from inside out in opposite directions and exhausting to the atmosphere. This cancels the axial thrust load and precludes the necessity for any ancillary seals that could pollute the test results. The seal journal diameter is 101.6 mm (4.000"). The upstream and downstream radial clearances of the tested damper seal are .102 mm (.004") and .203 mm (.008") respectively, while the configuration of the conventional seal is straight with .102 mm (.004") radial clearance. The first critical speed of the rotor-ball bearing support assembly is 3960 rpm (66 Hz) with no seal installed.

Instrumentation consists of two X-Y Bently proximity probes mounted on the bearing housing near the overhung end of the rotor. An air pressure transducer is installed into the inlet plenum between both seals to measure the inlet pressure. There is a flowmeter installed in the air supply line to measure the total mass flow rate (leakage). Rotor speed is measured by an optical pickup. Coastdown curve measurements are made by acquiring vibration displacement data from a Bently-Nevada synchronous tracking

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filter. A HP 3561A signal analyzer is used for logarithmic decrement measurements when conducting rap tests.

THEORY OF OPERATION

Alford (1965) published a theory to predict direct stiffness and damping coefficients of labyrinth seal with two blades and choked flow. The most notable prediction of Alford's analysis was that seals with clearances converging in the direction of flow would have negative damping, and seals with diverging clearances would have positive damping. The predicted coefficients are quite large. This theory modeled only the axial flow and neglected circumferential flow effects. Ten years of testing labyrinth seals at TAMU by Childs and Scharrer, 1988, and by Vance, et al., 1993, has shown that the direct damping coefficients of conventional labyrinth seals are very small, even with diverging clearances. Instead, the dominant rotordynamic coefficient of conventional seals is cross-coupled stiffness, which reduces the effective damping and can be destabilizing to rotor whirl. The reason for this failure of Alford's theory is that conventional labyrinth seals have continuous and unobstructed annular grooves so that pressure variations across the seal diameter cannot exist without large circumferential flow rates. Unfortunately, circumferential flow induces the destabilizing force represented by cross-coupled stiffness. The TAMSEAL design eliminates or greatly reduces the circumferential flow.

Iwatsubo (1980) made photographs through a transparent labyrinth seal wall that reveals a very complex flow pattern, containing vortices around the annulus. The TAMSEAL design makes this complex flow disappear, or at least makes it of secondary importance relative to the axial flow in and out the cavities. The current theory for the new damper seal design is therefore based on an assumption that the average pressure in the seal cavities can be calculated based on gross mass flow rates into and out of the cavities. Local flow fields within the cavities are ignored. This theory is mathematically the same as that developed by Sundararajan and Vance (1993) for a gas-operated bearing damper also invented at Texas A&M University. It is important to note that the new damper seal is unlike all other damping devices commonly used, in that it does not rely on viscosity of a fluid to dissipate energy.

A physical description of TAMSEAL phenomenon proceeds as follows:

Refer to Figure 1 and assume counterclockwise whirling of a rotor within the clearance circle of section "A-A". Consider the seal journal in the three o'clock position and moving up. The blade clearances adjacent to the p_3 and p_4 cavities are opening up. The clearances adjacent to p_1 and p_2 are closing. The percent rate of change of inlet area (at Pi on section "B-B") is greater than the percent rate of change of exit areas (at Pe on section "B-B"). The pressures in all cavities will therefore change with time, at the same frequency as the shaft whirl speed. It turns out that the dynamic pressure in each cavity leads the whirl displacement vector by a phase angle. If this phase angle is 90•, then the pressure force on the rotor will continuously oppose the rotor velocity. This is damping, by definition. The actual phase angle is frequency dependent and deviates considerably from 90• at high frequencies. The deviation from 90• reduces the damping and produces a negative stiffness coefficient that is small compared to typical shaft and bearing support stiffness in turbomachinery.

TEST RESULTS AND COMPARISON

The inlet air pressure to the seals was varied from 1 bar (14.7 psia) to 3.4 bar (50 psia) for the TAMSEAL, and from 1 bar (14.7 psia) to 4.4 bar (65 psia) for the conventional seal exhausting to the atmosphere. The inlet temperature was 23•C (74•F). The synchronous response to imbalance was measured by running the rotor up to 6,000 rpm, then decreasing the speed at a uniform rate, and recording the X and Y probe amplitudes as a function of the running speed. Figures 3 and 4 show how the maximum peak to peak amplitudes at the critical speed vary with inlet pressures. The coastdown results for a number of different inlet pressures are shown in Figures 5 through 10 respectively. The coastdown results show that the TAMSEAL has much more effective damping than the conventional seal. The TAMSEAL always has positive effective damping for imbalance response while the conventional seal has negative effective damping in the vertical direction. When inlet air pressure is above 3.1 bar (45 psia), the maximum amplitude of imbalance response for the TAMSEAL is decreased greatly, so that the coastdown curves are flat (no peak) in the horizontal direction. The effects of the TAMSEAL and the conventional seal on the critical speed are different from each other. The critical speed is raised with inlet air pressure for the conventional labyrinth seal. For the TAMSEAL, however, the critical speed first is lowered with inlet air pressure and then is raised with inlet pressure above 40 psia.

Rap tests of both seals were conducted with the rotor at rest for several different inlet pressures. Examples of the decaying vibration of rap tests of the TAMSEAL compared with the conventional labyrinth seal are shown in Figures 11 to 12. The rapidly decaying vibrations are with the TAMSEAL. Figure 13 shows logarithmic decrements extracted from these wave forms. When increasing the inlet air pressure to the seal, the damper seal was found to increase the logarithmic decrement sharply, while the conventional seal decreased the logarithmic decrement.

The mass leakage rates of the TAMSEAL and the conventional seal were also measured under identical conditions. The comparison of the leakage of both seals is shown in Figure 14. The leakage of the TAMSEAL is 1.30 times that of the conventional seal. The relationship between leakage and inlet air pressure is approximately linear for both seals, but the leakage rate of the TAMSEAL is increased more quickly with inlet air pressure than that of the conventional seal.

CONCLUSION

1. The TAMSEAL has much more equivalent damping for imbalance response than a conventional labyrinth seal with identical dimension, including whatever cross-coupled stiffness results from shaft rotation. Equivalent damping is indicated by reduction of the vibration amplitude at the critical speed.
2. For low inlet air pressure (2.7 bar and less), the TAMSEAL lowers the first critical speed frequency. When inlet air pressure is above 2.7 bar (40 psia), the TAMSEAL increases the first critical speed frequency. This is in contrast to the conventional labyrinth seal, which was found to always raise the critical speed.
3. For free vibration, the TAMSEAL has positive effective damping and increases the logarithmic decrement rapidly with inlet air pressure, while the effective damping of the conventional seal is not only very small, but becomes negative for inlet air pressure exceeding 2 bar (30 psia). When inlet air pressure is above 2.7 bar (40 psia), the effective damping of the TAMSEAL approaches the critical damping.
4. The leakage rate of the TAMSEAL is about 30% larger than that of a same dimension conventional labyrinth seal under identical conditions. The large damping effect of the TAMSEAL suggests that smaller clearances could be used in many applications, which would reduce the leakage. (Additional testing has shown that smaller clearances also produce higher damping).

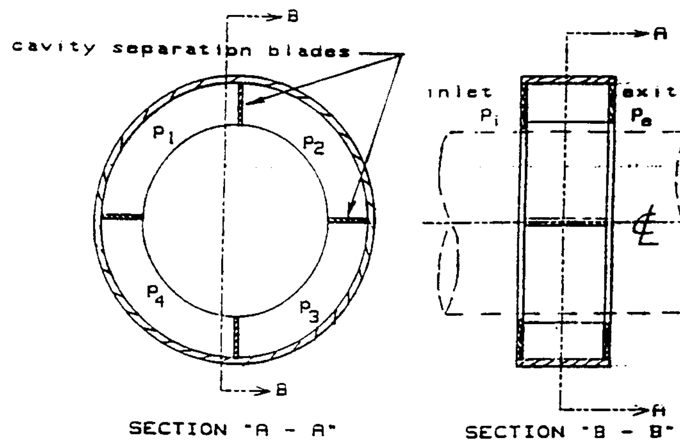

FIGURE 1. TWO-BLADED DAMPER SEAL

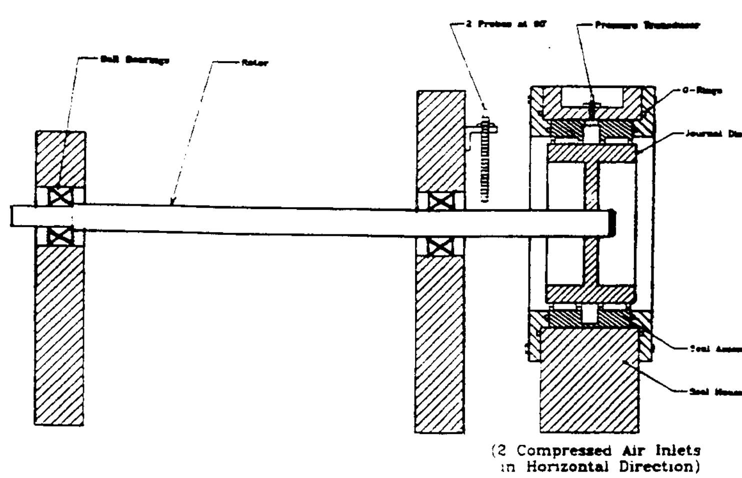

FIGURE 2. CROSS-SECTION OF DAMPER SEAL TEST RIG.

REFERENCES

Alford, J.S., "Protecting Turbomachinery from Self-Excited Whirl," *Journal of Engineering for Power*, Vol. 87, 1965, pp. 333-344.

Childs, D.W. and Scharrer, J.K., "Theory versus Experiment for the Rotordynamic Coefficients of Labyrinth Gas Seals, Part II-A Comparison to Experiment," *Journal of Vibration, Acoustics, Stress, and Reliability in Design*, Vol. 110, July 1988, pp. 281-287.

Iwatsubo, T., "Evaluation of the Instability Forces of Labyrinth Seals in Turbines or Compressors," NASA CP 2133, Workshop on Rotordynamic Instability Problems in High Performance Turbomachinery, College Station, Texas, May 12-14, 1980.

Vance, J.M. and Shultz, R.R., "A New Damper Seal for Turbomachinery," *Vibration of Rotating Systems*, ASME DE-Vol. 60, September 19-22, 1993.

Sundararajan, P. and Vance, J.M., "A Theoretical and Experimental Investigation of a Gas-Operated Bearing Damper for Turbomachinery-Part I: Theoretical Model and Predictions," proceedings of the 1993 ASME Vibration and Noise Conference, Albuquerque, New Mexico.

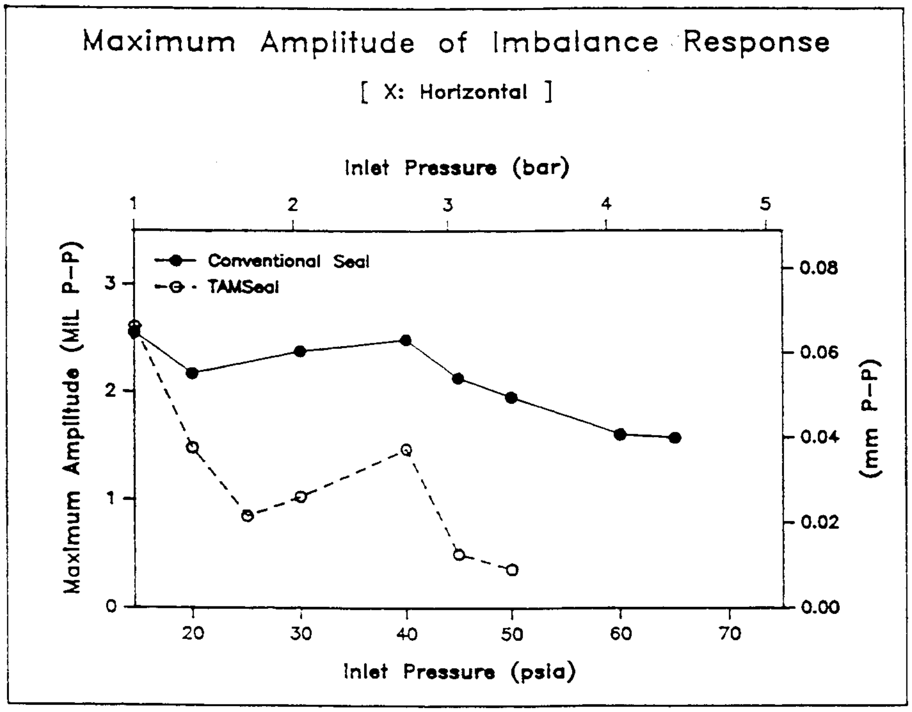

FIGURE 3. CRITICAL SPEED AMPLITUDE VS. INLET PRESSURE

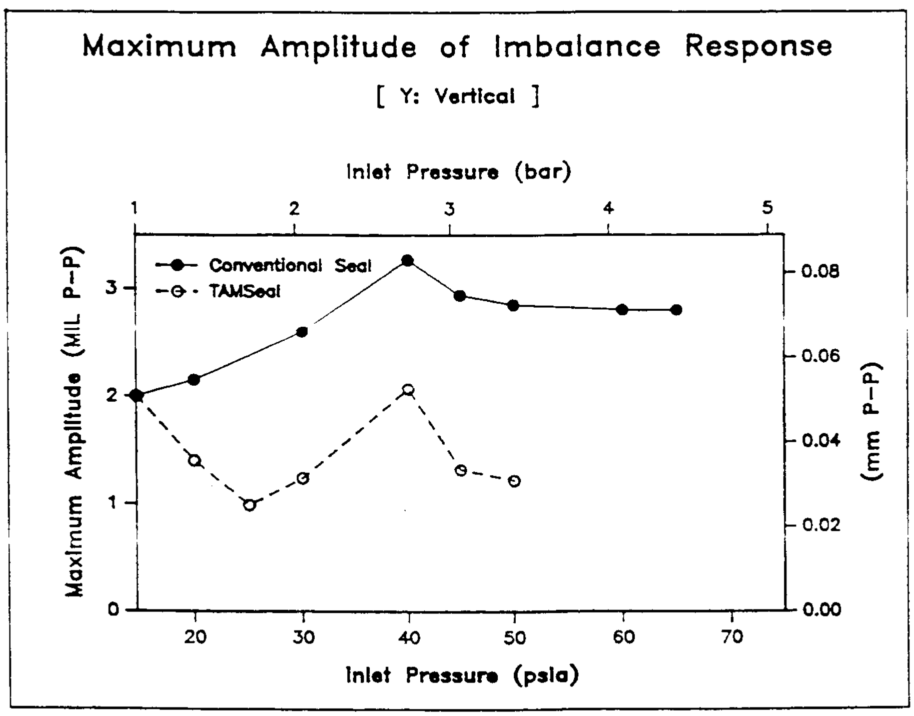

FIGURE 4. CRITICAL SPEED AMPLITUDE VS. INLET PRESSURE

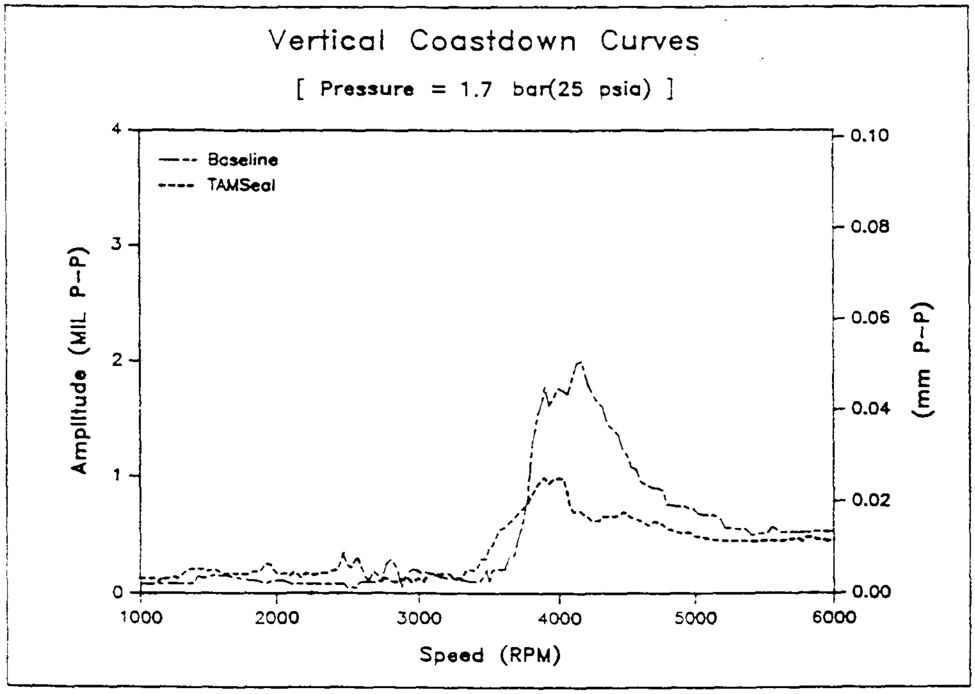

FIGURE 5. VERTICAL IMBALANCE RESPONSE (1.7 BAR)

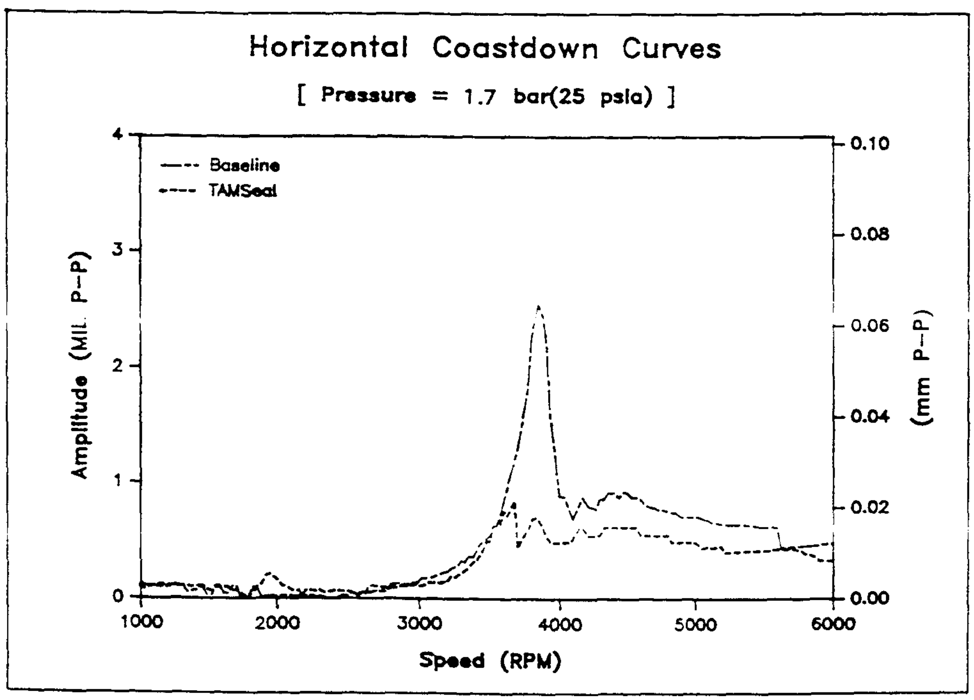

FIGURE 6. HORIZONTAL IMBALANCE RESPONSE (1.7 BAR)

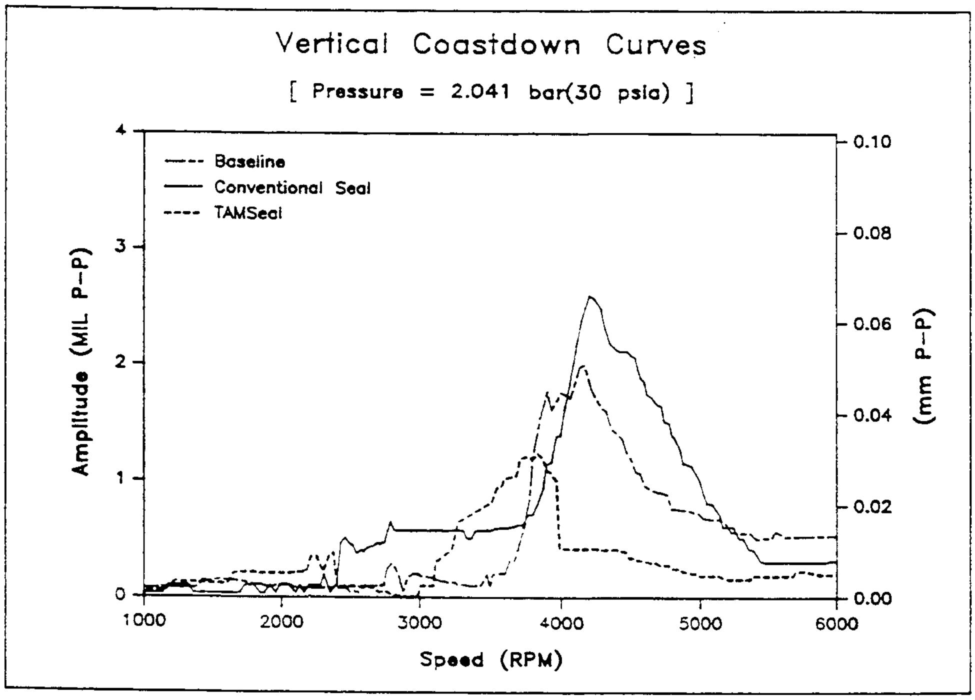

FIGURE 7. VERTICAL IMBALANCE RESPONSE (2.041 BAR)

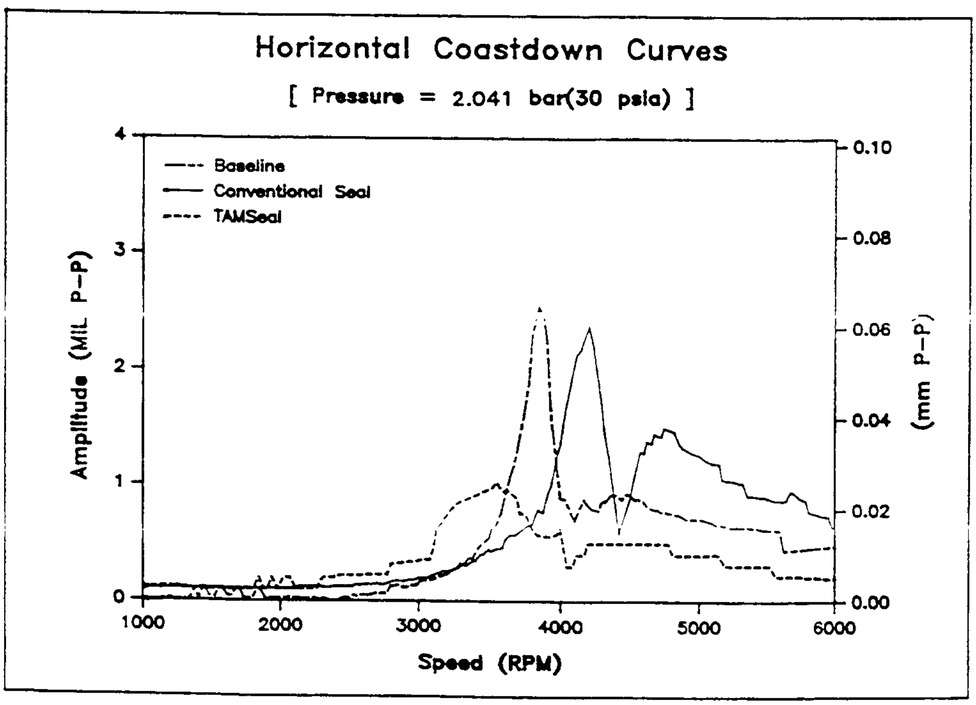

FIGURE 8 . HORIZONTAL IMBALANCE RESPONSE (2.041 BAR)

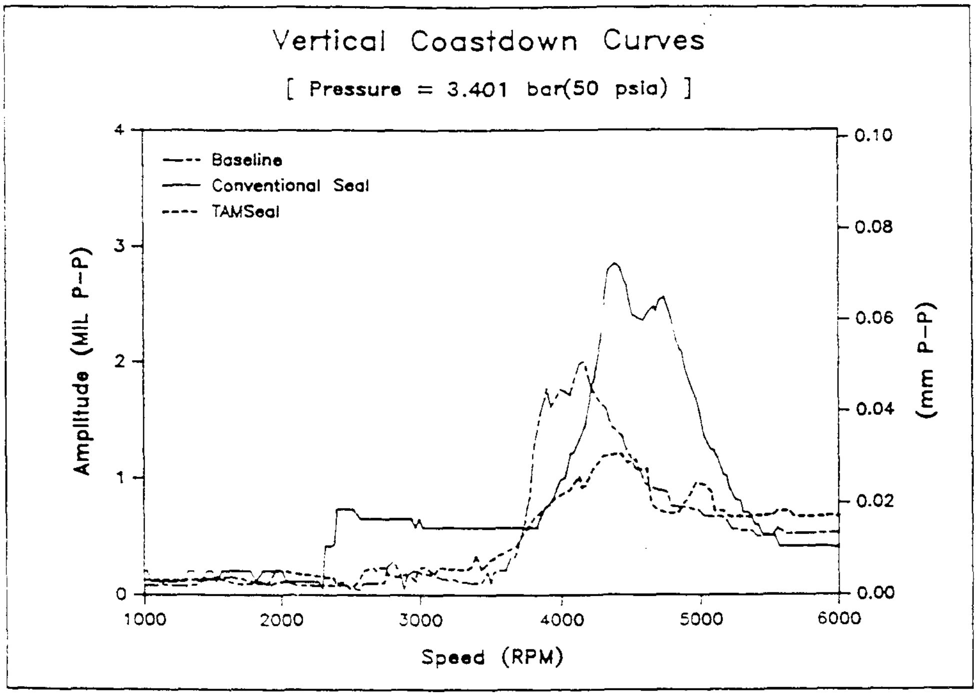

FIGURE 9. VERTICAL IMBALANCE RESPONSE (3.401 BAR)

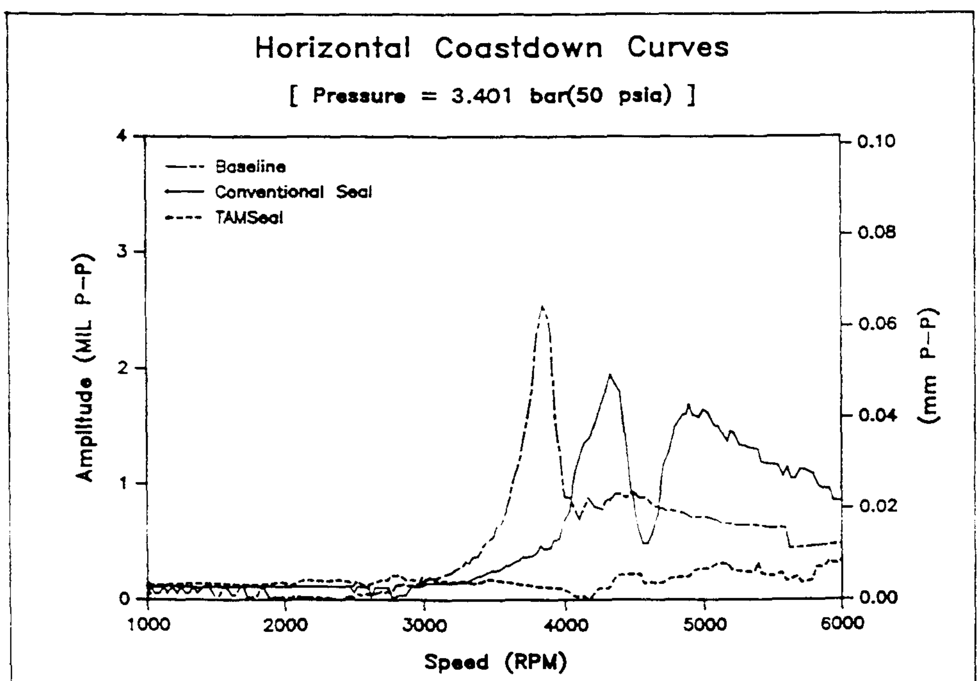

FIGURE 10. HORIZONTAL IMBALANCE RESPONSE (3.401 BAR)

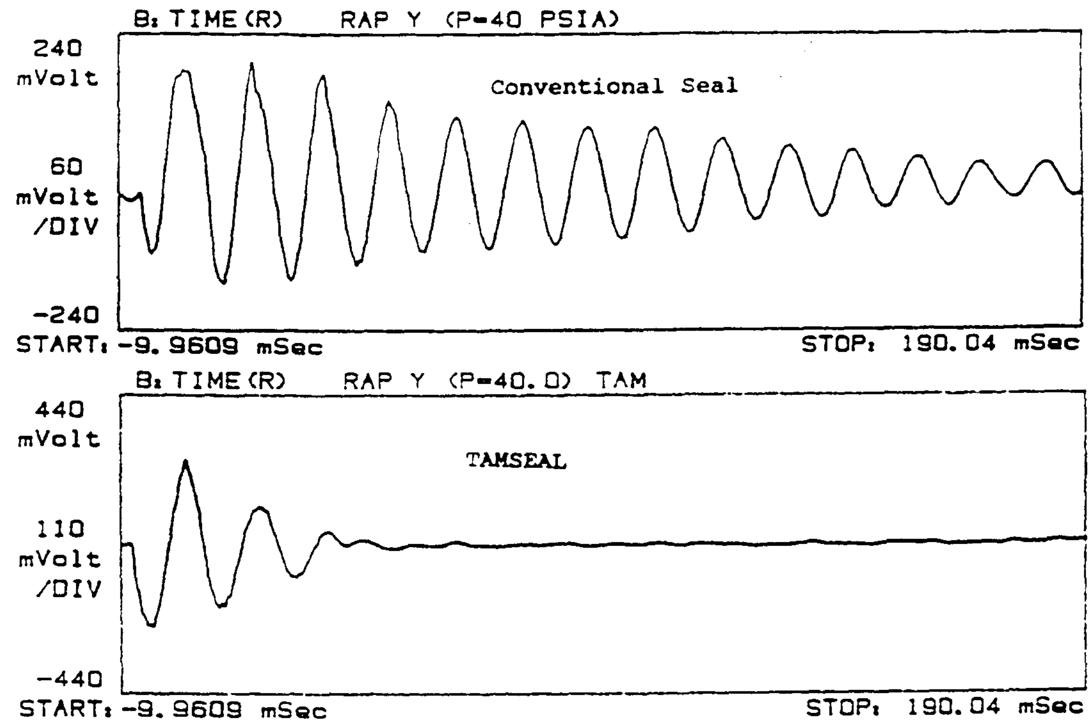

FIGURE 11. RAP TEST RESPONSE (2.721 BAR, VERTICAL)

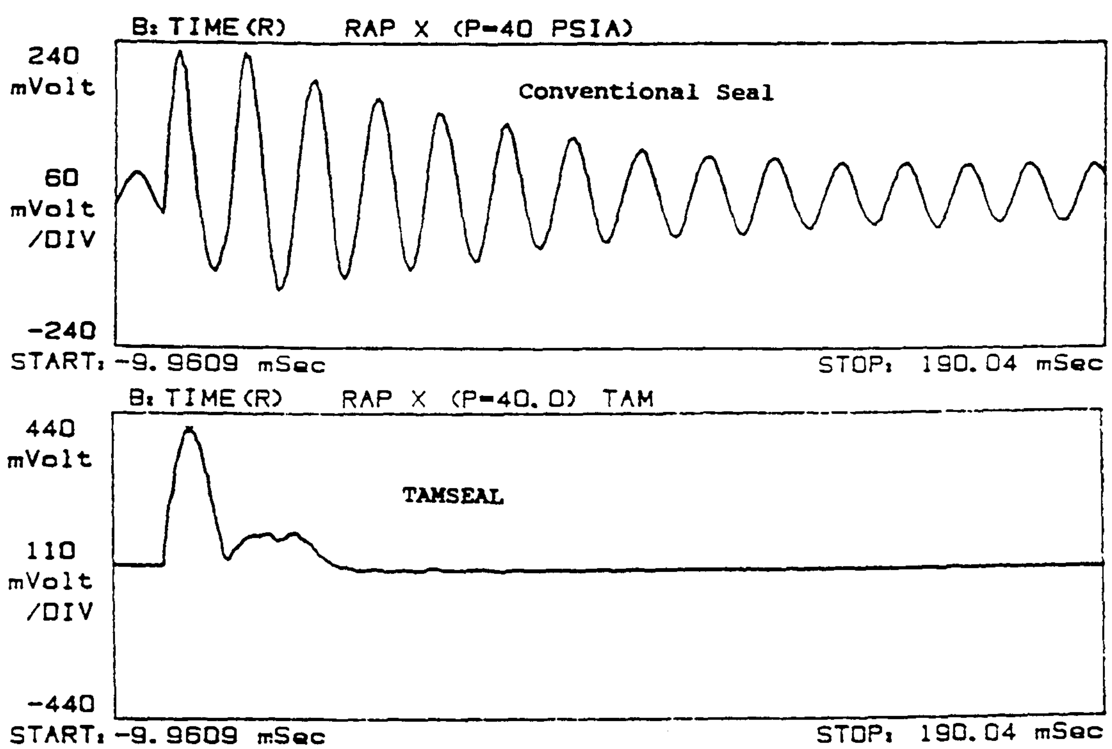

FIGURE 12. RAP TEST RESPONSE (2.721 BAR, HORIZONTAL)

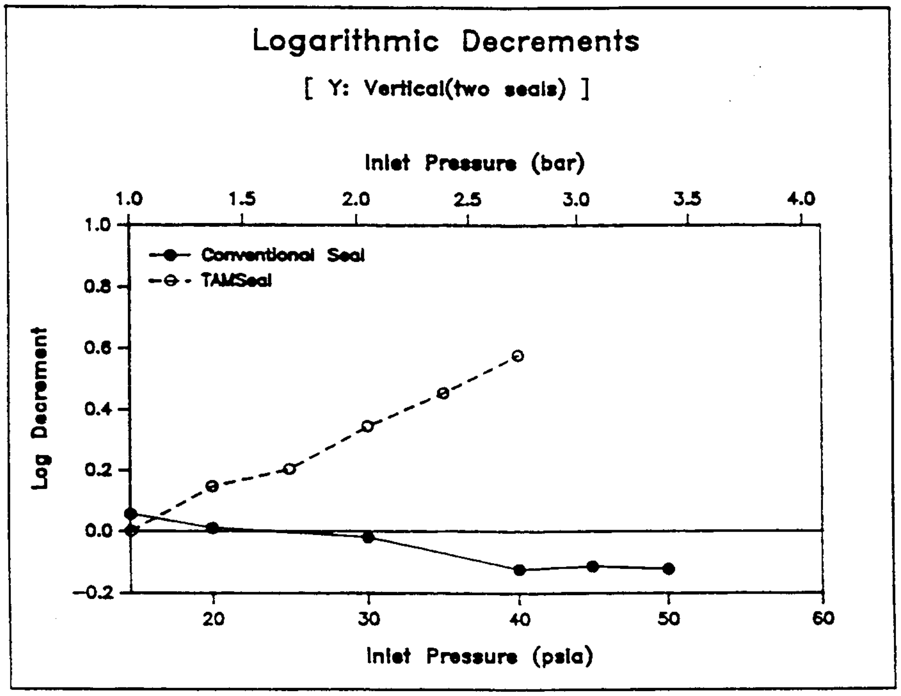

FIGURE 13. LOGARITHMIC DECREMENT (VERTICAL DIRECTION)

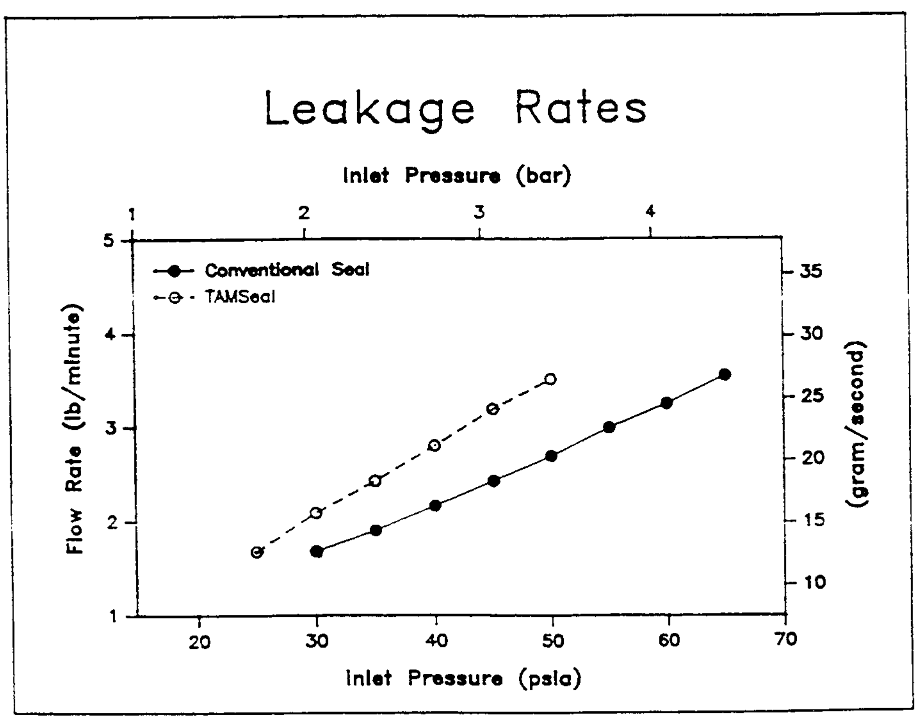

FIGURE 14 - LEAKAGE RATES VS. INLET PRESSURE