Wankel Rotary Engine's Apex Seal/Trochoid Wear Chatter *'the Devil's Nail Marks Persist'*

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Abstract- A problem existing since 55 years causes Wankel rotary engine to seize before it achieves operational loading conditions. Leading engine manufacturers like Ford, Curtiss Wright, and Bentley have studied this problem and have cited series of patents, but the cause of the problem remains unknown. Existing research literature shows one of the primary indications are the chatter marks, popularly known as 'the devil's nail marks', causing engine failure. The present study focuses on the root cause analysis of the chattering phenomenon occurring at the contact sliding interface between trochoid substrate and apex seal. An analogy drawn from Shobert's carbon-brush vibration and chatter analysis concludes coefficient of friction, being the driving cause of chatter initiation, is directly proportional to the angle between the contact elements.

Index Terms- Tribology, Chattering, Wear, Scuffing, Surface Roughness

I. INTRODUCTION

Felix Wankel patented the first rotary engine in 1929 with an idea to by-pass the traditional reciprocating piston motion. He wanted to achieve the four cycles – intake, compression, combustion, and exhaust while rotating, thus avoiding translating reciprocating motion into rotational motion. The steps towards research and development in rotary engines were taken in 1924, when Wankel was supported by the German Aviation Ministry and civil corporations to serve the national interest during World War II. Wankel, essentially, established the Institute of Engineering Study to develop rotary compressors. The idea turned to reality when he joined the prominent motorcycle manufacturer, NSU. In collaboration with NSU, the first Wankel engine of the type DKM rotary engine led to the birth of commercial rotary engines in 1957. Mazda, claiming itself as the sole automobile manufacturer in the world that produces rotary engine cars,[1] negotiated with NSU in 1961 to produce large number of Wankel engines for commercial use.[2,3,4,5]

"The Wankel engine has 48% fewer parts and about a third the bulk and weight of a reciprocating engine."[6] It uses no pistons, piston pins, piston pin retainers, connecting rods, connecting rod bearings, crankshaft, and piston rings.[7] "The four-stroke cycle events occur in a moving combustion chamber between the inside of an epitrochoid shaped housing and a trochoidal rotor with bow-shaped flanks."[8] Due to these characteristics, Wankel engines can achieve smooth and high engine operations.

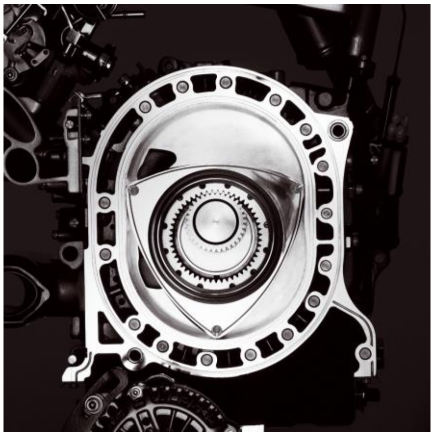

Figure 1: Rotary Combustion Engine[9]

Before Mazda could move forward with practical usage of Wankel engines in automotive use, there were number of problems that served as an obstacle, the chatter marks being the most prominent causes out of all, and thus the important area of interest in this review. Mazda's team of engineers working in collaboration with the NSU named these chatter marks, 'the devil's nail marks', causing the engine failure.

A. Trochoid Chattering

Chattering is a phenomenon that exists in a rotary engine caused by the vibrations between the apex seal and trochoid surface contact. The ripple-like marks called chatter are formed by the apex seals which were lifted off from the trochoid surface by a combination of events including combustion pressure and pushing of fuel and combustion residues along the surface; the seals would then touch down again with enough force to remove particles of the trochoid surface.[10] It affects the life and efficiency of the rotary engine and the engine components.

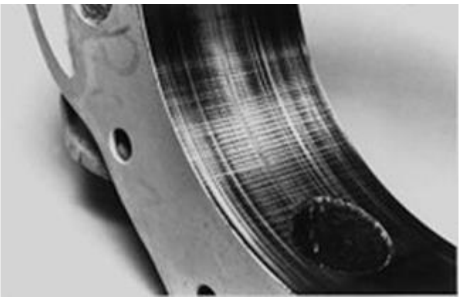

Figure 2: Trochoid chatter marks on Mazda's rotary engine[10]

B. Patents claiming chatter elimination via studying materials, coatings and lubricants

Fuhrmann E. and Frenzel M. claimed that the weight of the sealing bars play an important role in the formation of chatter marks. “According to the invention, it is proposed to make the radially acting sealing bars in the form of hollow members, thus permitting extremely light-weight bar-like sealing elements.”[11] Moskoqitz D. and Uy J. claimed inertial or dynamic mass weight of the seal element and the relative freedom from high interengaging friction as the two major aspects in the chatter problem. Their invention primarily focused on utilizing composition of materials, such as carbide, Nickel, Molybdenum disulfide etc, for the sealing element.[12]

Telang Y. and Uy J. invented a wear-resistant rotor housing for a rotary internal combustion engine by adding a coating of a mixture of martensitic stainless steel powder and a nickel-based alloy powder on the trochoid surface. The idea behind the invention was to achieve a stable hardness level of at least R_c 30 at operating temperatures of 400°F to minimize chatter.[13] Also, Jones C. found surface hardness a crucial factor in chatter elimination during his investigation to provide a liner of a wear resistant material on the inner surface of the trochoid wall to increase its wear life.[14]

Rogers T., Lemke W., Lefevre J, and Ohzawa T. performed a lubricants study to improve the efficiency and durability of rotary engines, addressing trochoid chatter wear.[10] Bedague P., Marchand P., Parc G., and Roux F. patented a method to lubricate 2-stroke engines and rotary engines. “The rotary engines fed with a fuel lubricant mixture, the fuel-lubricant compositions according to the invention are constituted to a conventional fuel from 50 ppm to 2% by weight with respect to said fuel.”[15] Also, it was found that the addition of specific organic compounds to the base lubricants results in a highly improved lubrication composition for a rotary engine.

C. Existing chatter in Wankel rotary UAV engines

The learning from the patents were utilized on the UAV rotary engines by the US Army and the engine still fails due to chattering. Two housings, LKI trochoid and Mazda RX-2, for the trochoid surface were tested for a duration of 100 hours, whose after-test measurements indicated substantial chattering on the trochoid surfaces leading to a complete engine failure (see LKI housing in figure 3 below).

Figure 3: Photograph of chatter marks after test operation of LKI trochoid housing

The patents fail to minimize contact surface temperature at the interface of apex seal and trochoid chatter and to minimize/eliminate the frictional energy generated at the sliding interface. Thus, the conclusion was drawn that the problem exists in identifying potential root cause of rotary engine trochoid chatter and that the understanding of parameters accounting for chattering is still lacking.

D. Carbon-brush friction and chatter

Chattering, in general, can be seen as a result of rotary motion between the seal and trochoid surface that causes vibrations leading to chatter marks. These marks are caused due to friction, which was theoretically frame worked by Shobert. He conducted a mechanical brush holding experiment and found that different positions of the brush to the armature i.e. leading, radial, or trailing, results in a unique friction pattern. He also found that the angle between the brush and the armature plays an important role in determining the range of friction causing chatter.[16]

In this paper a systematic approach to evaluate materials, coatings, and lubricants and their combination to remove frictional heat (thermal energy) developed at the interface of the trochoid surface and the apex seal would be utilized. Materials and coatings would be identified that would eliminate friction at the sliding interface to maintain lubricant/additive chemistry. High modulus trochoid material with an objective on minimizing micro deflection of trochoid surface when chatter occurs would be of interest. Advanced fabrication methods, focusing additive manufacturing, would be taken into consideration majorly accounting towards cost reduction. The proposed solutions would aim to achieve an extended MTO target of 1000 hours with reduced fuel consumption, reduced power, and reduced engine cost.

II. TECHNICAL CONCEPTS AND METHODOLOGY – EFFECTS OF VARYING PARAMETERS ON ENGINE PERFORMANCE

A. Effect of angle variation on chatter initiation

Variation in electrical voltage was measured for varying positions of the brush against the armature. It was found that when the brush was positive as leading brush, as shown in figure 4, chatter resulted as a loss of voltage due to brush chatter on the voltage graphical readings (figure 5).

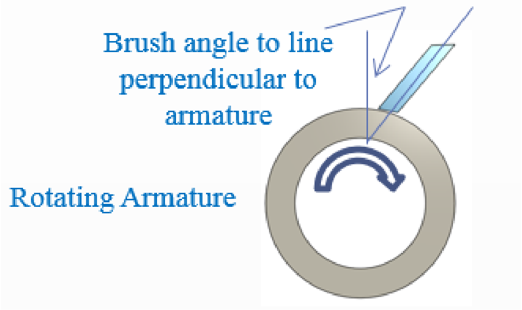

Figure 4: When brush is positive as leading brush (Chatter/Noise)

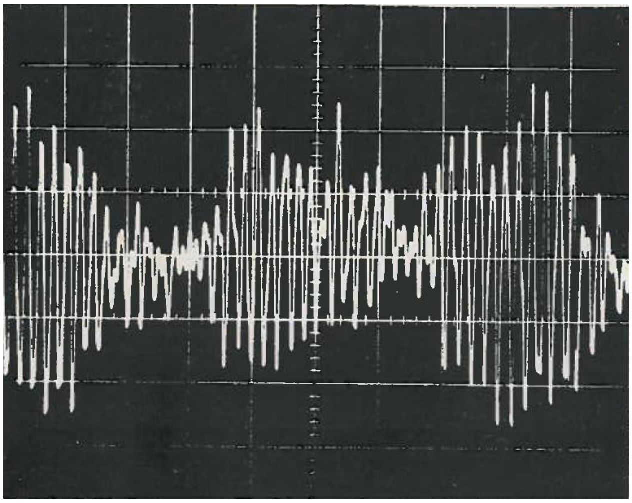

Figure 5: Vibration in electrical voltage (Chatter/Noise)[16]

Alternatively, when the brush was positive as trailing brush, as shown in figure 6, uniform electrical voltage was measured indicating no chatter (figure 7).

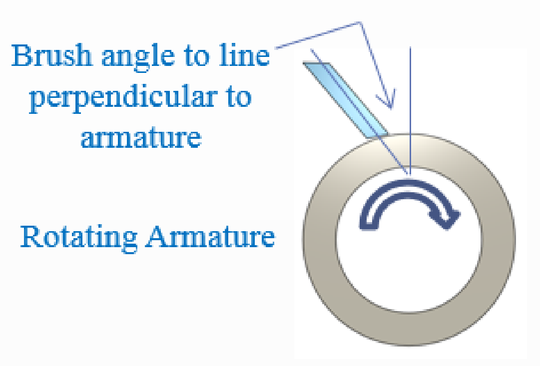

Figure 6: When brush is positive as trailing brush (No chatter)

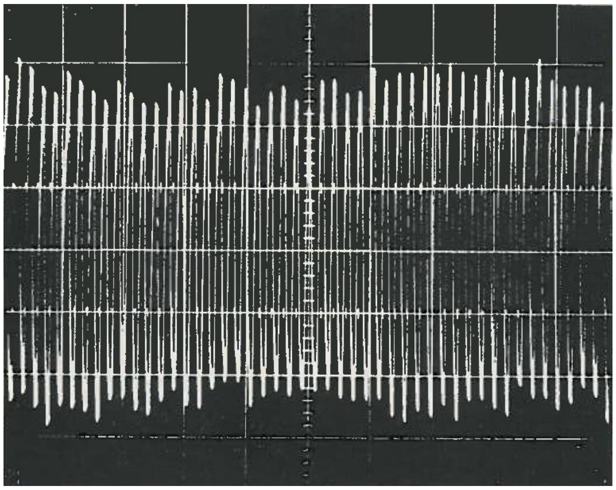

Figure 7: Uniform electrical voltage (No chatter)[16]

B. Chatter angle varying as function of coefficient of friction

The phenomena described above was theoretically formulated to describe relationship between coefficient of friction and the angle between centerline of brush and normal to armature, which comes out to be:

$$\theta = tan^{-1}\mu \qquad \text{Eq. 1}$$

where,
μ = coefficient of friction
θ = angle between centerline of brush and normal to armature

Equation 1 provides a valuable relationship indicating possible range of angles that results in chatter initiation in effect of friction, as shown in figure 8. It can be deduced that for large coefficient of friction magnitudes, the chatter start occurring at relatively large angles or vice-versa. The chatter angles were obtained using equation 1 for varying coefficient of friction, example, a friction of 0.1 yields an angle of 6^0, 0.2 yields 12^0, and 0.4 yields 22^0 etc . Thus, it gives an urge to lower the coefficient of friction, i.e. "zero friction", to minimalize/eliminate chatter by bringing the chatter angle to zero.

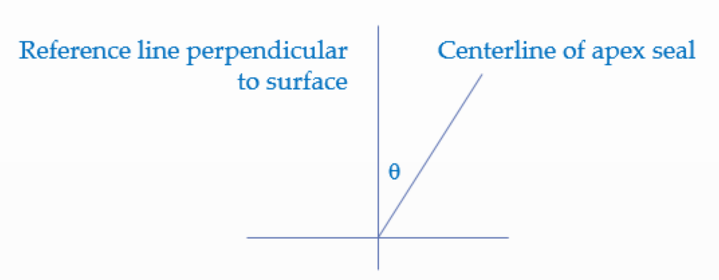

Figure 8: Effect of coefficient of friction μ on range of angle θ that chatter occurs

C. Analysis of root cause of trochoid chatter caused by apex seal in Wankel rotary engine

The brush chatter experimentation provides an analogous phenomenon that occurs in Wankel rotary engine. The chatter that was made to occur in Shobert's mechanical system serves as a model to depict the trochoid chatter caused by the apex seal in Wankel rotary engine and thus serves as a potential root cause of the trochoid chatter problem. Figure 9 indicates the geometry relationship of apex seal centerline position with respect to instantaneous normal of line perpendicular to trochoid surface varies as the rotor rotates.

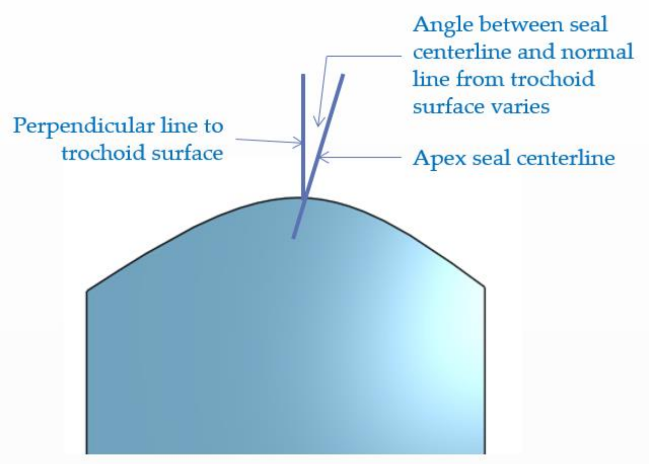

Figure 9: Angle between centerline of apex seal and normal to trochoid surface

As the apex seal travels making contact with the trochoid surface, the angles between seal centerline and normal line from trochoid surface vary simultaneous to the travel motion, as shown in figures 10 and 11. These ranges of angles constitute critical chatter angle, where chatter occurs, depending on the coefficient of friction existing between the two contact surfaces.

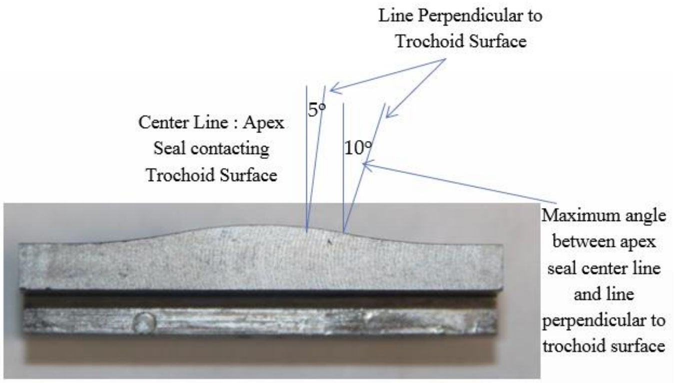

Figure 10: Varying angle between apex seal centerline and line normal to trochoid coupon surface

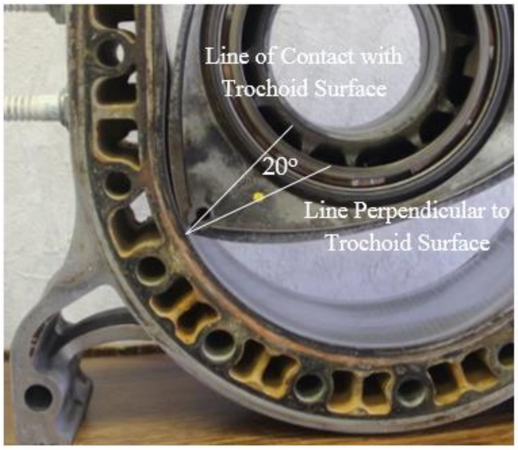

Figure 11: Varying angle between rotatory apex seal and line perpendicular to trochoid surface of Wankel rotary engine

III. PROPOSED ANALYTICAL SOLUTIONS

A. Proposed solution to eliminate trochoid chatter

Having identified the root cause for the existing chatter in Wankel's rotary engine, possible steps could be taken to eliminate the underlying cause. As understood, the contact angle between the trochoid surface and the apex seal serves as a determining parameter of chatter existing region that corresponds to the critical chatter angle experimentally derived by Shobert. For a matter of fact, it was concluded that critical chatter angles are affected in relationship to the friction coefficient, and thus corresponding to the thermal energy developed at the contact interface of trochoid surface and apex seal.

$$Thermal\ Energy\ developed\ in\ sliding\ system \approx \frac{\mu * S * F}{A}$$

Eq. 2

where,

μ = coefficient of friction
S = Speed
F = Force/Load applied
A = Area

The equation 2 identifies possible parameters considered responsible in affecting the thermal energy developed at the interface of the contact surfaces. Analyzing the parameters for the operational range of a typical rotary engine would constitute towards the thermal energy multiplication factor, it is found that the friction co-efficient is the dominant factor, typically in the range of 0.02 to 0.15 constituting a thermal energy multiplication factor of 75X. Thus, it imposes a potential need to address coefficient of friction to achieve determined thermal energy for the engine efficiency thus eliminating trochoid chatter developing at the sliding interface.

For the trochoid substrate, HTCS-150 Hard and A-2 Tool Steel would be the participating candidates chosen based on the following desirable properties fulfilled:

- Inherently high modulus of elasticity. Modulus of elasticity at the surface can be increased by plasma ion nitriding.
- Ion implantation
- High thermal conductivity
- Can be machined/ground utilizing conventional purposes
- Substantial bond between plated/frame sprayed materials
- Molten aluminum can be bonded to surface

For the trochoid surface, Non/limited Hydrogenated DLC (Diamond-Like Carbon) coating, Nikasil with Diamond particles, and Ion Implanted CRC Chromium Plate would serve as test coatings in combination to the trochoid substrate materials. The properties achieved by the chosen trochoid coatings are:

- Low coefficient of friction
    - Inherent friction
    - When in present of friction modifiers in oil

- Bulk temperature capability >800°F (maintains hardness and strength)
- High thermal conductivity
- High modulus of elasticity
- High yield strength
- Required minimum preparation of base support material
- Limited or no secondary finishing subsequent to application

For the lubrication, Synthetic Group V Base Stocks comprising Esters and Polyalkylene Glycols would be considered, as they are polar and can absorb on metal surfaces providing substantial lubrication without additives. However, additives can also be utilized to increase the effectiveness of the resulting system. Some of the properties aimed at by the lubricants to influence coefficient of friction would constitute of the following:

- Base fluid technology
- Additive chemistry
- Viscosity
- Bulk/instantaneous temperature at interface of opposing surfaces
- The relative sliding speed of the opposing surfaces which could be sliding or rolling, or a mixture of both
- The chemistry of the opposing surfaces
- Conformal or non-conformal contact between opposing surfaces
- Contact pressure
- Surface roughness

Advanced fabrication methods are considered one of the major players in the research. Additive manufacturing, in particular, would be of interest to achieve the following desired requirements:

- Allow fabrication of complex parts at reduced cost
- Shorter lead time
- No assembly required
- Easy to implement changes
- Fewer constraints

B. Numerical Analysis - Computational and experimental simulation approach

In the search of materials that can perform effectively at high temperatures by reducing wear and friction, several dry-film lubricants and materials have been tested for friction and wear measurements in bench tests for comparison. However, it is found difficult to model sophisticated properties of the lubricants and advanced materials being utilized on CAD supported software to perform finite element analysis. A research performed as part of the PhD dissertation at the Air Force Institute of Technology where coatings were studied to analyze material damage when impacted under high energy. The actual test sled was simulated on LS-DYNA3D and the test codes were written and compared using CTH, ABAQUS, and LS-DYNA3D.[17] The simulation incorporated materials and coatings only, where no lubricants were considered as part of the designed model. It was found that the characteristics of the lubricants and the additives, if involved, imposes limitations to numerically simulated model to identify unknown properties as part of the parameter definition, which gets reflected to the simulated outcomes. Thus, experimentation has proved much successful over computer-aided simulations where advanced lubrication, additives, and friction modifiers are utilized as part of the system.

In this study, LS-9 bench fixture, shown in figure 12, would be utilized, which is a tester that simulates engine conditions for testing different materials, lubricants, liner, and ring combinations. It incorporates apex seals in a holder loaded with two cut trochoid engine surface segments (coupons) positioned 180° apart. The seal holder reciprocates with a stroke of about 1-in and lubricant is introduced to the wear interface periodically by a peristaltic pump. The entire unit can be heated to the required temperature up to 470°C. Pre-test and post-test surface measurements/traces of the coupons and seals are used to determine the amount of wear developed whilst a data acquisition system calculates the coefficient of friction.

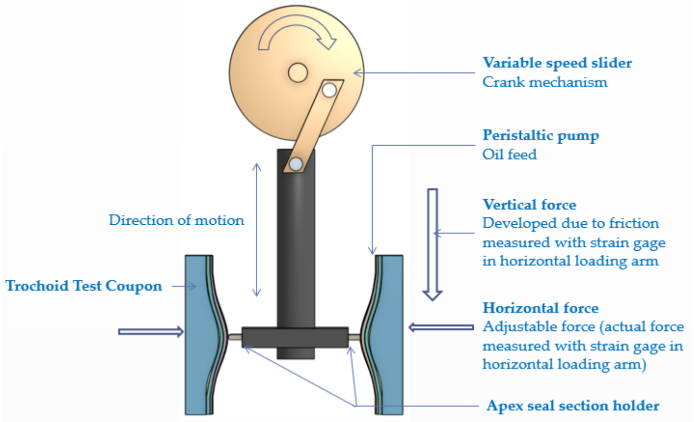

Figure 12: LS-9 Wear Test Bench Fixture identifying critical parameters that can be adjusted and automated during testing

The test specimen utilized would be of a trochoid shape to analyze the effect of change in angular contact between the trochoid surface and the apex seal, as depicted by the rotary engines. The test specimens would make use of the combination of materials and coatings as identified for the runs of extended duration in addition to advanced lubricants forming a thin layer at the contact interface of the sliding system, as shown in figure 13. Factors pictured in figure 12 that includes varying bulk temperature, peak velocity at the sliding test surfaces, rate of oil feed, and trochoid design to constitute range of angle between apex seal centerline to line perpendicular to trochoid surface would be utilized against testing the specimen (figure 13). The range of these parameters are listed in table 1.

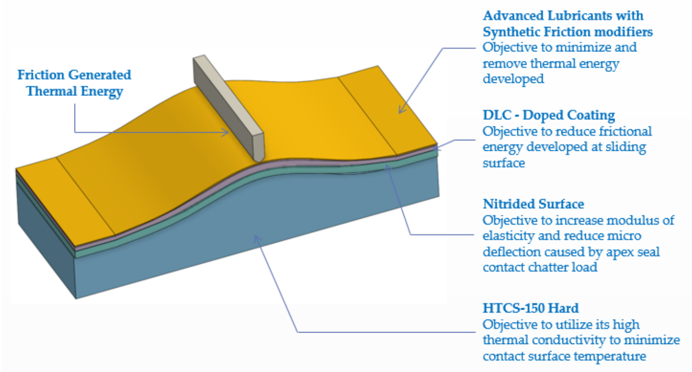

Figure 13: Concept fixture duplicating apex seal and trochoid engine surface sliding system

Table 1: LS-9 Test Parameters Limit

Parameters	Range of Parameters Applicable to LKI Apex Seal/Trochoid Surface	System Overall Capabilities
Bulk Temperature	RT, 250-300°F	RT-750°F
Surface Pressure between Apex Seal/Trochoid Coupon	255 PSI	0-2,315 PSI
Relative Sliding Velocities between two test surfaces	Peak Velocity: 4.36 ft/s (1.33 m/s) Mean Piston Speed: 52.92 ft/s (16.13 m/s)	Peak Velocity: 6.99 ft/s (2.13 m/s) Mean Piston Speed: 169.32 ft/s (51.61 m/s)
Rate of Oil Feed to sliding surfaces	0-0.5 ml/hr (0.01 g/min) Scale Rate: 0-0.565 in/min (14.351 mm/min)	0 – 1.32 ml/hr (0.02 g/min) Scale Rate: 0-1.489 in/min (37.82 mm/min)
Range of angle of apex seal centerline to line perpendicular to trochoid coupon surface	0-10 degrees	With coupon modifications 0 - 25 degrees

It would be expected that a reduction in coefficient of friction at the sliding interface of the system would be measured indicating elimination of trochoid chatter. As a motivation, a UK based developer of advanced formulation of base stocks/additive for two cycle engine named Croda, managed to achieve a coefficient of friction as low as 0.02 making use of advanced friction modifiers (polymeric) in chemistry to DLC coating. A graphical comparison between commercial oil and the effect of additive chemistry utilizing friction modifiers in interaction with DLC coating to test against coefficient of friction is shown in figure 14 below.[18,19]

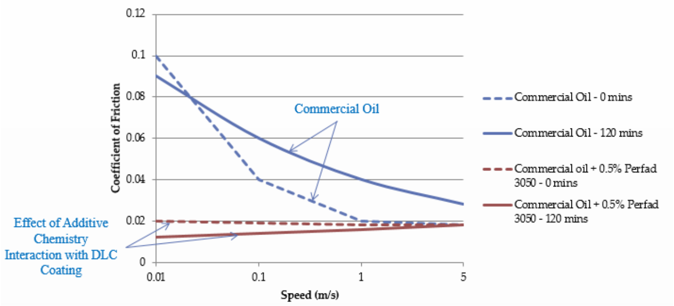

Figure 14: Example of interaction of lubricant/additive with sliding surface to reduce friction (per Croda)[18,19]

IV. CONCLUSION

In this paper, coefficient of friction has been identified as a root cause of chattering in rotary engines. The proposed solutions are targeted at reducing friction coefficient outside of the chatter zone. Bench testing is planned for this research to confirm the hypothesis for the existence of trochoid chatter marks observed in Wankel rotary engines and to validate the recommended solutions against chatter elimination.

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