The NorEaster Engine/ Power System

Differentiating Otto cycle (or Clerk cycle) IC engines from turbines, as presented in the introduction, is a straightforward matter and already the object of myriad trade studies that have segmented the power system market and led to turbine application for helicopters above about 2500lbs and piston engines for helicopters<2500lbs. Consequently, the objective of this section shall be to introduce the NorEaster in the context of its features and benefits relative to piston engines and to demonstrate how its unique characteristics allow for a lighter power system, superior performance, and lower lifecycle cost, enabling practical application of smaller rotorcraft UAVs.

A conventional crank-conrod engine of any stroke-cycle has three basic moving parts per cylinder: crank, connecting rod (conrod), and piston. The conrod introduces a strong second harmonic (and smaller fourth, sixth, and other even harmonics) into all the inertial functions: force, torque, and moment (with multiple cylinders). These harmonics can cause vibration in engines with small numbers of cylinders or odd cylinder configurations. The transverse component of wrist-pin force from the conrod's angularity introduces side force on the piston skirt and cylinder wall, which can cause increased friction and wear.

The NorEaster cam engine has only two basic moving parts per cylinder: cam and piston-rod assembly. The piston-rod assembly is in pure translation, thus introduces no additional harmonics, and it also adds no transverse force between piston and cylinder. Two concentric cams on nested concentric shafts are driven by pairs of rollers arranged on either side of each piston rod such that the downward motion of the piston drives one cam CW and the other CCW. This gives simultaneous, concentric counterrotation, which is ideal for rotorcraft.

If the cam function used is simple harmonic motion (SHM) with no dwells, then for each cam, there will be only a primary harmonic component in all the inertia functions except torque. But inertial torque of the counterrotating cam is of opposite sign and cancels the inertial torque as felt at the rotors and airframe. With other cam functions that contain higher harmonics, the arrangement of the NorEaster's pistons in opposed pairs cancels all harmonics of inertia force including the first, making it perfectly force-balanced. If the pistons are all coplanar, as is true in the NorEaster engine, then there is also zero inertial shaking moment. In either engine, there will still be higher harmonics of the gas force and gas torque functions, and their inertia torques can have nonzero even harmonics. Again, counterrotation cancels the reaction torque on the airframe. Only the camshaft experiences these oscillations internally. The equations for this analysis are all derived in reference iv.

The geometry of a vee or opposed multi-cylinder engine is defined as shown in Figure 4 (from ref iv, p. 730). This geometry is valid for either a crank engine (as shown) or a cam engine. The reference X-axis is taken in the mid plane between the cylinders and the Y-axis is orthogonal through the crank or cam center. Unit vectors **r**-hat and **n**-hat are defined, respectively, along and normal to the piston axis of the right bank, and vectors **l**-hat and **m**-hat are, respectively, along and normal to the piston axis of the left bank. Bank angle γ defines the angular offset of each cylinder bank from the X-axis. An opposed configuration has $\gamma = \pm 90°$. The angle θ is the crank or cam angle, and is defined, for any cylinder, as $\omega t - \varphi_i$, where φ_i is the phase angle of the ith cylinder, n is the number of cylinders, ω is shaft angular velocity, m_B is the moving mass, r is crank radius, and t is time.

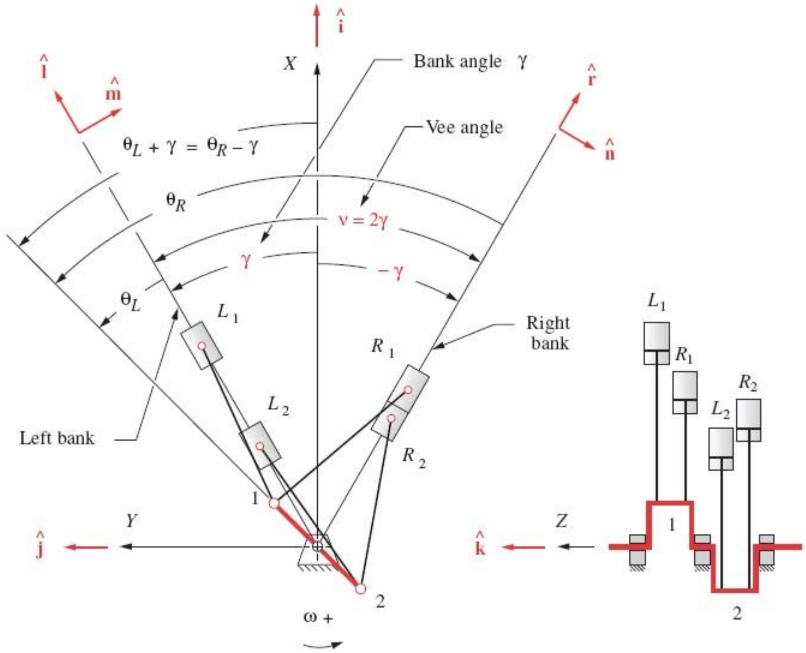

Figure 4: Geometry of a Vee or opposing cylinder piston engine

The expressions for inertial shaking force F_s in right and left banks can be shown to be:

$$\mathbf{F}_{\mathbf{s}_R} \cong m_B r\omega^2 \begin{bmatrix} \left(\cos\omega t\cos\gamma - \sin\omega t\sin\gamma\right)\sum_{i=1}^{n/2}\cos\phi_i \\ +\left(\cos\omega t\sin\gamma + \sin\omega t\cos\gamma\right)\sum_{i=1}^{n/2}\sin\phi_i \\ +\dfrac{r}{l}\left(\cos 2\omega t\cos 2\gamma - \sin 2\omega t\sin 2\gamma\right)\sum_{i=1}^{n/2}\cos 2\phi_i \\ +\dfrac{r}{l}\left(\cos 2\omega t\sin 2\gamma + \sin 2\omega t\cos 2\gamma\right)\sum_{i=1}^{n/2}\sin 2\phi_i \end{bmatrix} \hat{\mathbf{r}}$$

$$\mathbf{F}_{\mathbf{s}_L} \cong m_B r\omega^2 \begin{bmatrix} \left(\cos\omega t\cos\gamma + \sin\omega t\sin\gamma\right)\sum_{i=n/2+1}^{n}\cos\phi_i \\ -\left(\cos\omega t\sin\gamma - \sin\omega t\cos\gamma\right)\sum_{i=n/2+1}^{n}\sin\phi_i \\ +\dfrac{r}{l}\left(\cos 2\omega t\cos 2\gamma + \sin 2\omega t\sin 2\gamma\right)\sum_{i=n/2+1}^{n}\cos 2\phi_i \\ -\dfrac{r}{l}\left(\cos 2\omega t\sin 2\gamma - \sin 2\omega t\cos 2\gamma\right)\sum_{i=n/2+1}^{n}\sin 2\phi_i \end{bmatrix} \hat{\mathbf{l}}$$

These vectors in the planes of the cylinder banks are combined vectorially to obtain their vector components in the XY planes with:

$$F_{s_x} = \left(F_{s_L} + F_{s_R}\right)\cos\gamma\ \hat{\mathbf{i}}$$

$$F_{s_y} = \left(F_{s_L} - F_{s_R}\right)\sin\gamma\ \hat{\mathbf{j}}$$

$$\mathbf{F}_\mathbf{s} = F_{s_x}\ \hat{\mathbf{i}} + F_{s_y}\ \hat{\mathbf{j}}$$

These equations as shown are taken out only to the second harmonic of the driving function, but they can be expanded to include any number of harmonics as desired. A sufficient, but not necessary, condition for zero inertial shaking force is that the summations of the trigonometric functions of the phase angles as shown in the equations must all be zero:

$$\sum_{i=1}^{n}\cos\phi_i = 0 \qquad \sum_{i=1}^{n}\sin\phi_i = 0$$

$$\sum_{i=1}^{n}\cos 2\phi_i = 0 \qquad \sum_{i=1}^{n}\sin 2\phi_i = 0$$

Even absent this condition, the bank angle γ can cause certain components of shaking force to be zero: The X components will all be zero when γ = 90°. These equations can be shown to give zero shaking force for all harmonic components in an engine with any number of opposed pairs of cylinders (γ = 90°), arranged radially at equiangular spacing. Any periodic function can be approximated by a Fourier series carried out to a desired number of terms (harmonics). Thus, any cam function selected to drive the NorEaster cam engine will result in theoretically exact force balance.

In a conventional inline or vee crank engine, the cylinders must be spaced apart along the crankshaft axis, as shown in Figure 4, to allow the various crank throws to pass by one another. This gives the potential for unbalanced shaking moments to exist about an axis transverse to the crank axis, as defined in equations 14.11 in reference iv. The cam engine does not have this limitation. All cylinders are in the same plane and consequently do not generate any moments about transverse axes.

There will also be an inertial shaking torque in either a crank or cam engine. Its equations are:

$$\mathbf{T}_{i21_R} \cong \frac{1}{2} m_B r^2 \omega^2 \left[\begin{array}{l} \frac{r}{2l}\left(\sin(\omega t+\gamma)\sum_{i=1}^{n/2}\cos\phi_i - \cos(\omega t+\gamma)\sum_{i=1}^{n/2}\sin\phi_i\right) \\ -\left(\sin 2(\omega t+\gamma)\sum_{i=1}^{n/2}\cos 2\phi_i - \cos 2(\omega t+\gamma)\sum_{i=1}^{n/2}\sin 2\phi_i\right) \\ -\frac{3r}{2l}\left(\sin 3(\omega t+\gamma)\sum_{i=1}^{n/2}\cos 3\phi_i - \cos 3(\omega t+\gamma)\sum_{i=1}^{n/2}\sin 3\phi_i\right) \end{array} \right] \hat{\mathbf{k}}$$

$$\mathbf{T}_{i21_L} \cong \frac{1}{2} m_B r^2 \omega^2 \left[\begin{array}{l} \frac{r}{2l}\left(\sin(\omega t-\gamma)\sum_{i=n/2+1}^{n}\cos\phi_i - \cos(\omega t-\gamma)\sum_{i=n/2+1}^{n}\sin\phi_i\right) \\ -\left(\sin 2(\omega t-\gamma)\sum_{i=n/2+1}^{n}\cos 2\phi_i - \cos 2(\omega t-\gamma)\sum_{i=n/2+1}^{n}\sin 2\phi_i\right) \\ -\frac{3r}{2l}\left(\sin 3(\omega t-\gamma)\sum_{i=n/2+1}^{n}\cos 3\phi_i - \cos 3(\omega t-\gamma)\sum_{i=n/2+1}^{n}\sin 3\phi_i\right) \end{array} \right] \hat{\mathbf{k}}$$

These show the first three harmonics of inertial torque. For them to be zero, sufficient conditions are:

$$\sum_{i=1}^{n/2}\sin\phi_i = 0 \qquad \sum_{i=1}^{n/2}\cos\phi_i = 0 \qquad \sum_{i=n/2+1}^{n}\sin\phi_i = 0 \qquad \sum_{i=n/2+1}^{n}\cos\phi_i = 0$$

$$\sum_{i=1}^{n/2}\sin 2\phi_i = 0 \qquad \sum_{i=1}^{n/2}\cos 2\phi_i = 0 \qquad \sum_{i=n/2+1}^{n}\sin 2\phi_i = 0 \qquad \sum_{i=n/2+1}^{n}\cos 2\phi_i = 0$$

$$\sum_{i=1}^{n/2}\sin 3\phi_i = 0 \qquad \sum_{i=1}^{n/2}\cos 3\phi_i = 0 \qquad \sum_{i=n/2+1}^{n}\sin 3\phi_i = 0 \qquad \sum_{i=n/2+1}^{n}\cos 3\phi_i = 0$$

For a crank or cam engine constructed of pairs of opposed cylinders, for each opposed pair, all odd harmonic terms of inertia torque including the fundamental will be zero, but all even harmonics may be nonzero unless the cam function is simple harmonic motion, in which case there will be only a second harmonic of inertia torque as shown in Figure 5. But, all of these torque components are cancelled by the counterrotating cam. This is a significant advantage of the cam engine over a crank engine that can only give counterrotation through a gearbox, which adds its own harmonics.

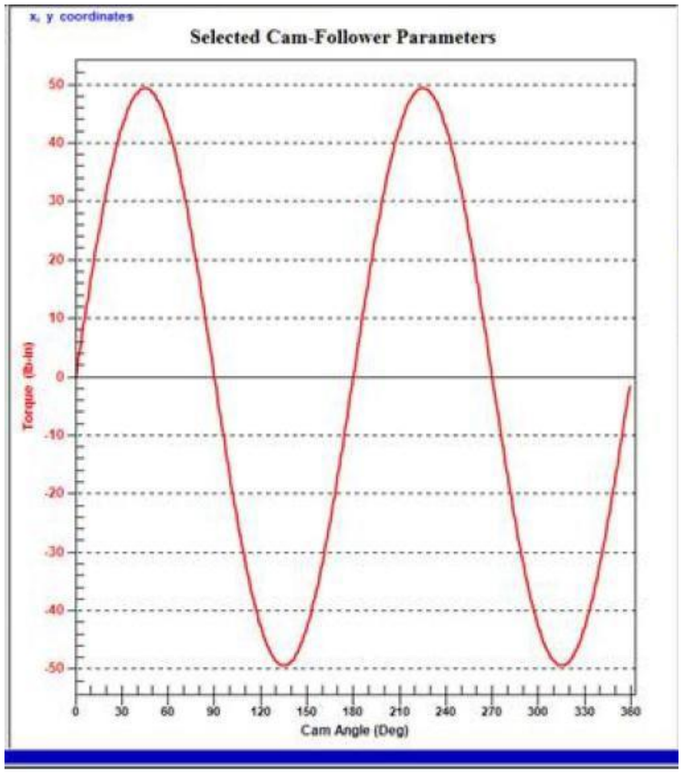

Figure 5: Inertia Torque for a One-Lobe, Symmetrical SHCCam Over One Revolution

A crank engine has piston displacement, velocity, and acceleration functions whose shapes for any one cylinder, and thus its Fourier components, are completely defined by its bore/stroke ratio and crank/conrod ratio. An example of these functions is shown in Figure 6 over two revolutions of the crank. Note the distortion of the shapes from the large second harmonic due to conrod oscillation. The bottom plot shows the gas force for a two-stroke engine, firing once per revolution. Figure 7 shows the inertia torque function for a two-cylinder opposed crank engine over two revolutions of the crank. As shown it includes the first three harmonics of the function, all of which are nonzero.

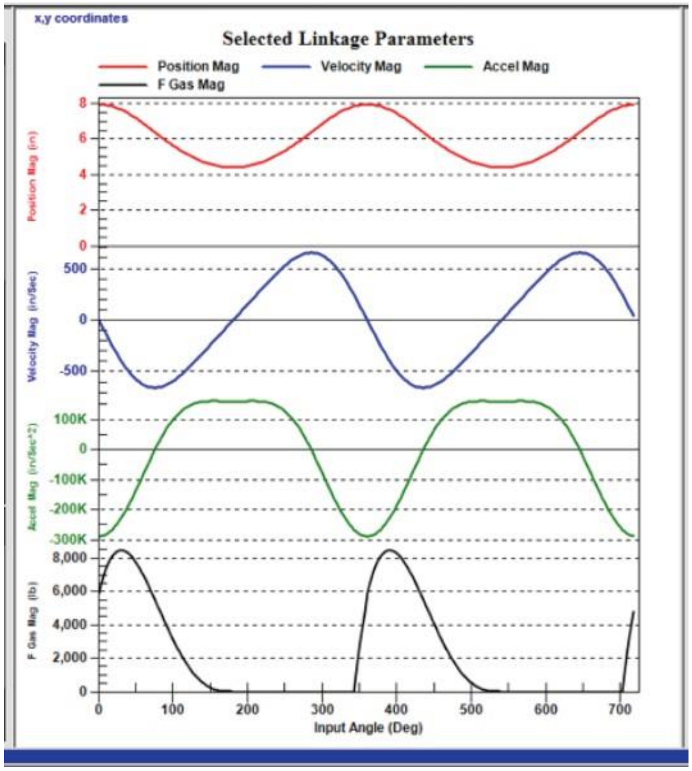

Figure 6: From top to bottom: Piston Displacement, Velocity, Acceleration, and Gas Force in a Crank Engine

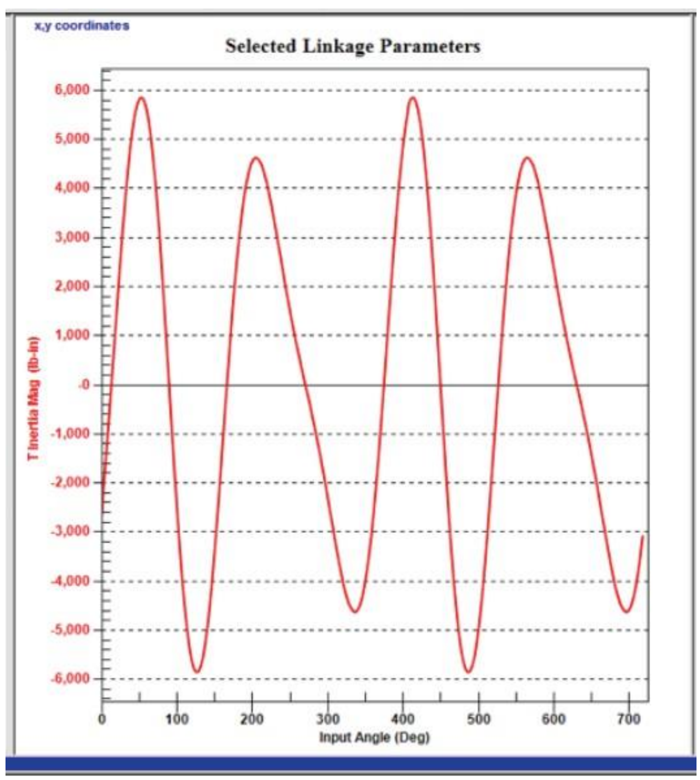

Figure 7: Inertia Shaking Torque in a Two-Cylinder Opposed Crank Engine

The NorEaster cam engine, on the other hand, can tailor these piston functions with variation in the cam profile. The simplest arrangement is a symmetrical, simple-harmonic-motion rise and fall cam as shown over one revolution in Figure 8. This mimics a Scotch-yoke mechanism, which is, in effect, a crank engine with an infinitely long conrod. Both of these mechanisms have pure harmonic motion. Figure 9 shows that its functions are symmetric, continuous, pure harmonics in all derivatives. All derivatives contain only the fundamental frequency, which due to the four-lobe cam is four times the cam rotational speed, i.e, piston speed with one piston per cam. Figure 5 shows the inertial shaking torque function for a one-lobed, SHM cam, which is a pure second harmonic. A multi-lobed SHM cam such as the one in Figure 8 will have a single harmonic at 2X the number of followers (pistons), i.e, an eighth harmonic for this four-lobed cam, assuming one cylinder per cam. Again, these harmonics will be cancelled by the counterrotating cam.

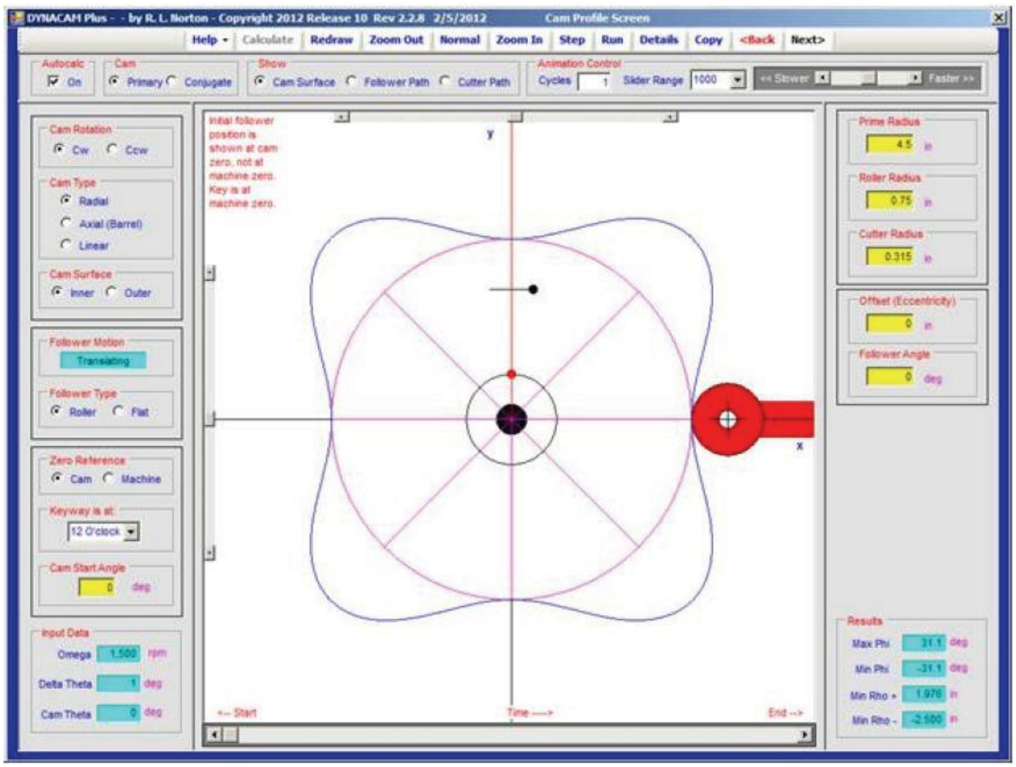

Figure 8: Four-Lobe Symmetrical SHM Cam for the NorEaster Engine

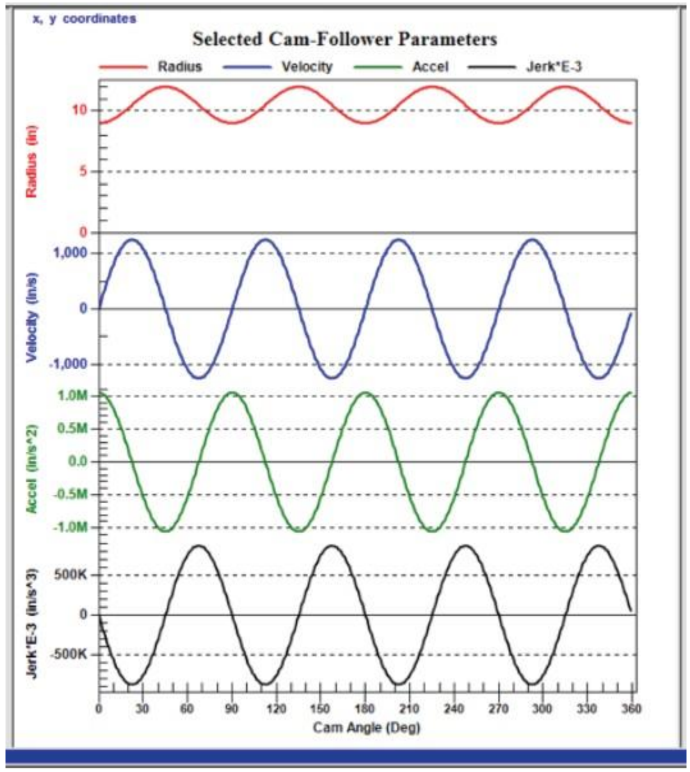

Figure 9: From top to bottom: SHM Displacement, Velocity, Acceleration, and Jerk in a Cam Engine

If desired, the NorEaster piston motion can be made asymmetric and be tailored to take maximum advantage of flame-front travel rate, fluid dynamics of the intake system, or other desired parameters. An asymmetric cam is shown in Figure 10. The velocity profile of the piston on either the up or down stroke can be varied within broad limits using sophisticated motion functions such as B-splines as shown in Figure 11. It is possible that knock control in a compression-ignition engine can be effected by shaping of the piston velocity profile near top dead center (TDC). This will introduce higher harmonics in the driving function, the even members of which can show up in the shaking torque. One of the goals of the proposed study is to determine the efficacy of variation in cam profile on control of power delivery from the exploding charge to the motion conversion mechanism of this unique and versatile cam engine and its effect on the engine's specific fuel consumption, among other factors.

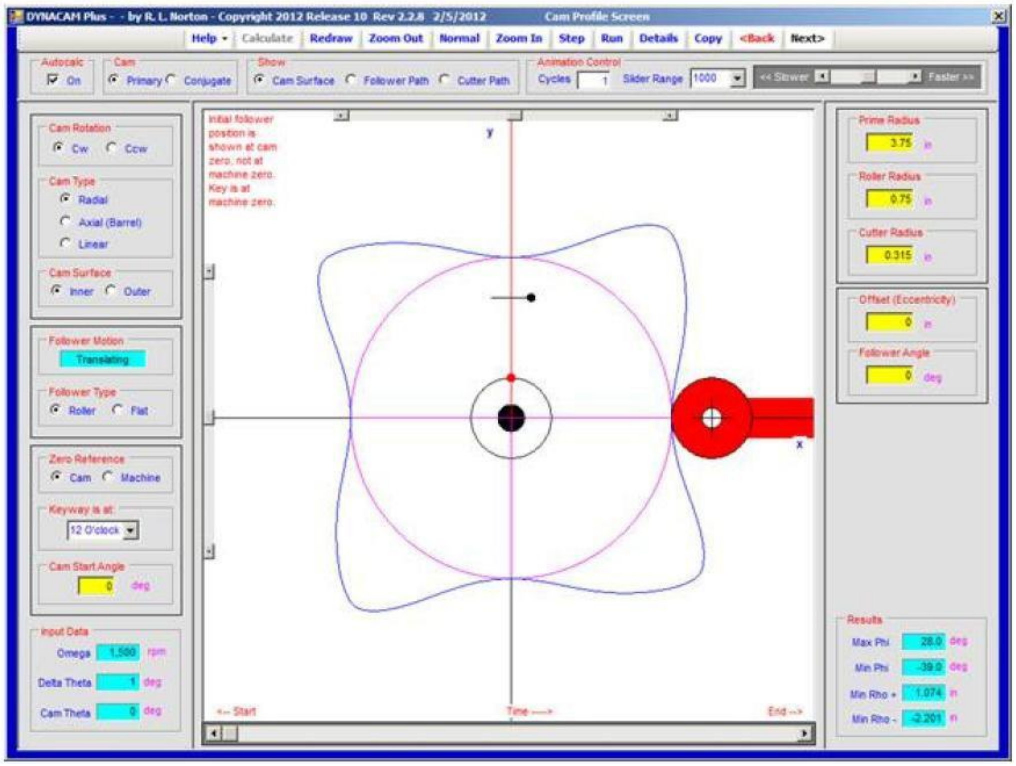

Figure 10: An Asymmetric, Four-Lobe Spline Cam for the NorEaster Engine

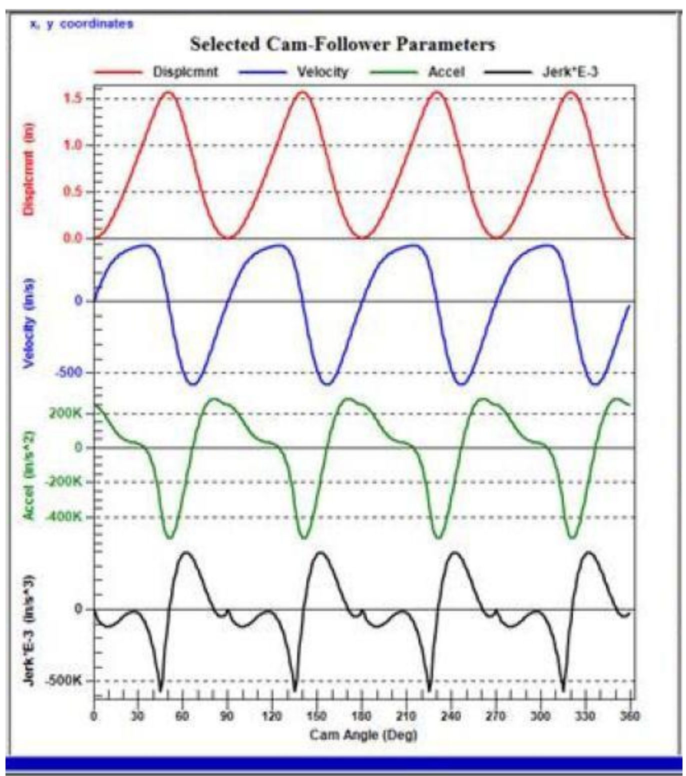

Figure 11: From top to bottom: Position, velocity, acceleration and jerk for an Asymmetric, Four-Lobe Spline Cam

In addition to its superior balance state and resulting low vibration, the major advantage of the NorEaster cam engine is its allowance of simultaneous counter-rotating output. This eliminates the need for a tail rotor and its associated shaft, gearing and airframe structure. This constitutes a significant weight saving as well as a reduction in complexity and overall vehicle size. Another advantage is that having multiple lobes on the cam gives an inherent gear reduction ratio between piston speed and output shaft rotational speed. The engine is essentially an integrated power source and speed reduction unit. It does not need an external gearbox. With a four-lobe cam, which can accommodate eight cylinders, piston speed will be four times that of cam rotation. This feature is particularly well-suited to the requirements of slow-turning helicopter rotors and pistons traveling at optimum velocities for power generation. For example, with a four-lobe cam driving rotors at 1000 rpm, the pistons will be operating at an effective 4000 rpm, thus being in a better range for thermodynamic efficiency, power, and torque output.

In summary, the trade space for piston vs. turbine power systems is already established and divided into two segments where turbines are the superior solution for larger rotorcraft, while piston engines trade favorably for rotorcraft <2500lbs. The NorEaster provides a significant improvement over the current piston engine segment on a stand-alone basis of low-vibration operation, power/weight by removal of gear reduction transmission, and overall simplicity of design. Further benefits accrue at the system level from ability for counter-rotation, tail rotor removal, and expected overall packaging efficiency and impact on overall rotorcraft design. Consequently, it is anticipated that not only will the NorEaster enable more practical application of smaller rotorcraft in the 50hp range, but also that it may very well extend the trade space for piston engines in rotorcraft beyond the 2500lbs range due to its improved power/weight over conventional piston engines and its other associated system benefits.

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Professional Background and Experience: Mr. Norton is a registered professional engineer in Massachusetts. He has over 50 years' experience in engineering design and manufacturing and over 40 years experience teaching mechanical engineering, engineering design, computer science, and related subjects at Northeastern University, Tufts University, and WPI. Norton has been on the faculty of WPI since 1981, and is currently the Milton P. Higgins II Distinguished Professor Emeritus. He is also the founder and president of Norton Associates Engineering Consultants since 1970.

At Polaroid Corporation for 10 years, he designed cameras, related mechanisms, and high-speed automated machinery. He spent three years at Jet Spray Cooler Inc., designing food-handling machinery and products. For five years he helped develop artificial-heart and noninvasive assisted-circulation devices at the Tufts New England Medical Center and Boston City Hospital. Since leaving industry to join academia in 1974, he has continued as an independent consultant on engineering projects ranging from disposable medical products to high-speed production machinery. He holds thirteen U.S. patents.

He is the author of numerous technical papers and journal articles covering kinematics, dynamics of machinery, cam design and manufacturing, computers in education, engineering education, and of the texts *Design of Machinery, Kinematics and Dynamics of Machinery, Machine Design: An Integrated Approach,* and the *Cam Design and Manufacturing Handbook*. He is a Fellow of the American Society of Mechanical Engineers and a member of the Society of Automotive Engineers. In 2007, he was selected as a *U. S. Professor of the Year* by the *Council for the Advancement and Support of Education*

(CASE) and the *Carnegie Foundation for the Advancement of Teaching*, who jointly present the only national awards for teaching excellence given in the United States of America.