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A COMPUTATIONAL MODEL OF IMPACT LOADING IN A MODULATING RECIPROCATING COMPRESSOR

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ABSTRACT

During 1997-1998, a new type of reciprocating compressor was developed which allows an air conditioning system in which it is applied to produce cost effective capacity modulation. This new type of compressor uses a rotating eccentric to disengage a cylinder. The eccentric mechanism is allowed to freely switch from one driving point on the crankshaft to another when the motor switches direction of rotation. The starting torque of the motor accelerates the crankshaft to collide with the eccentric at considerable velocity. It was necessary to know the magnitude of this force to properly design the eccentric. Calculating the magnitude of the force imparted to the eccentric was a design challenge, and a computational model was created to simulate the impact system. A valuable design tool was thereby created which allowed prototype cycle reduction and helped generate a robust design.

INTRODUCTION

In general, capacity modulation allows improved creature comforts for the end user, better reliability and increased system efficiency. An air conditioning system that uses this new type of compressor can provide capacity modulation at a lower applied cost than prior technology.

This modulating compressor provides full capacity when the crankshaft is rotated in one direction, and part capacity when rotated in the reverse direction. This is made possible by a rotate-able eccentric which disengages one cylinder. This eccentric is driven by stops on the crankshaft. Figure 1 shows the mechanism engaged in one cylinder mode (No Stroke on switchable cylinder). Figure 2 shows the crankshaft rotating and switching modes. Figure 3 shows two-cylinder mode (Full Stroke).

When the motor reverses rotation direction, the crankshaft rotates away from one eccentric stop, and collides with the other stop. This collision delivers significant impact loads onto the mechanism. In trying to quantify this loading, standard methods of approximating impact force were found to be insufficient due to the complex part geometry.

The functionality and reliability of the eccentric mechanism is critical to the success of this modulating compressor. Therefore, to create a reliable design, being able to understand and predict the loading on the mechanism was vital. The design tool chosen to facilitate this was a computational model of the impact system. This paper will summarize the method used to generate this model and discuss how it was used to develop a reliable and successful mechanism.

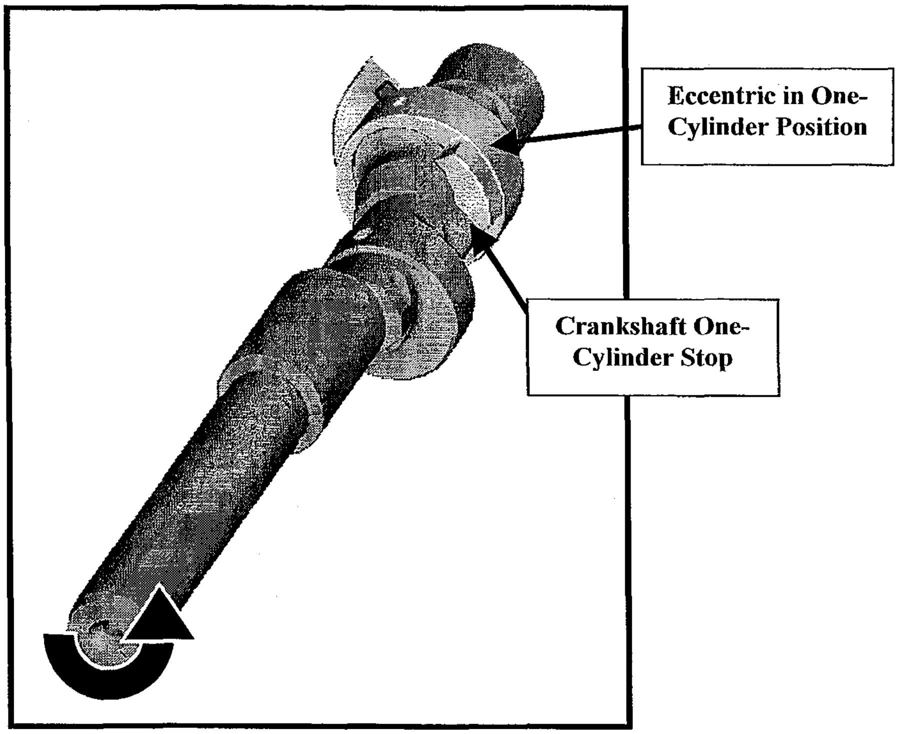


Figure 1

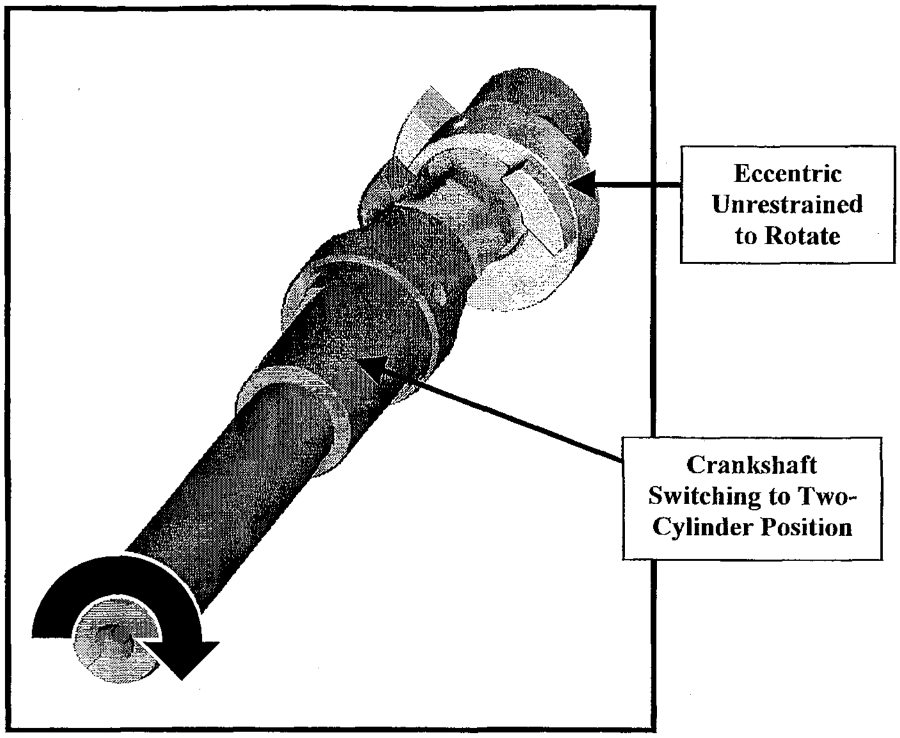


Figure 2

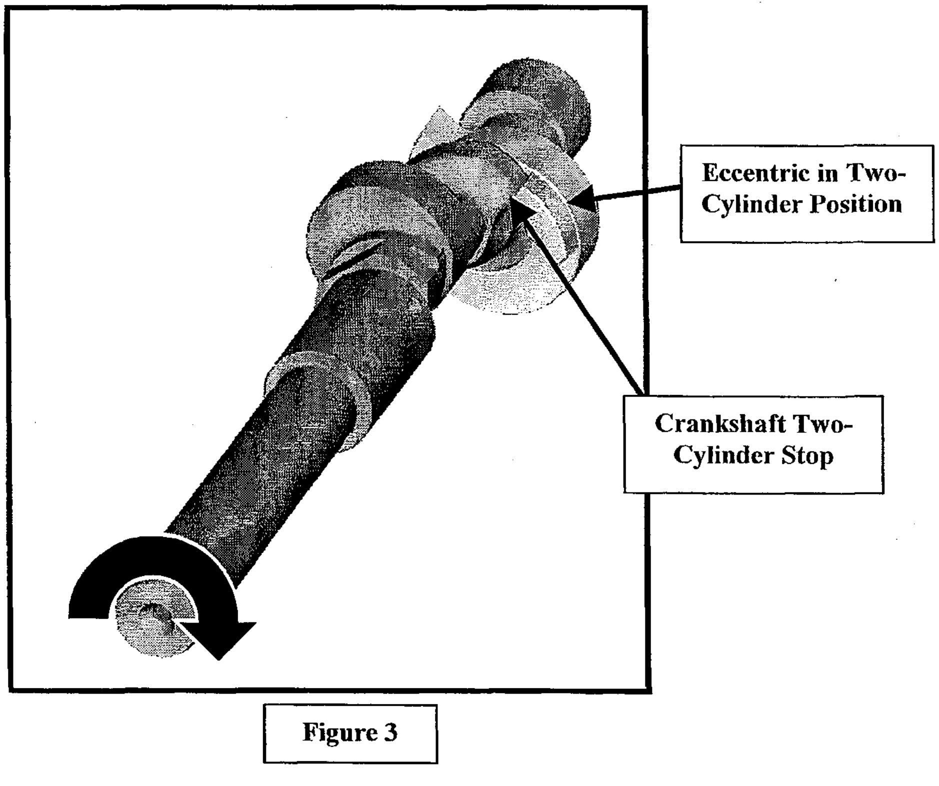


Figure 3

METHOD TO GENERATE COMPUTATIONAL MODEL

- Step 1: Inspect the mechanical system and write the differential equations which govern it. Put in terms of the highest derivative as shown in Equations 1 and 2. The right hand side of these equations will serve as the input for the acceleration terms, and we can integrate these to get velocity and position. Figure 4 labels the properties of the parts. The key idea behind these equations is that the impacting parts will slightly deform each other at the stops. As this happens, the parts will behave as a spring-mass-damper system and can be modeled as such.

Equation 1: $$\ddot{\Theta} = \frac{T(\dot{\Theta}) - K_Q r - C_{t1}(\dot{\Theta} - \dot{\Phi})}{J_o}$$

Equation 2: $$\ddot{\Phi} = \frac{C_{t2}\dot{\Phi} - K_{t2}\Phi + K_Q r + C_{t1}(\dot{\Theta} - \dot{\Phi})}{J_1}$$

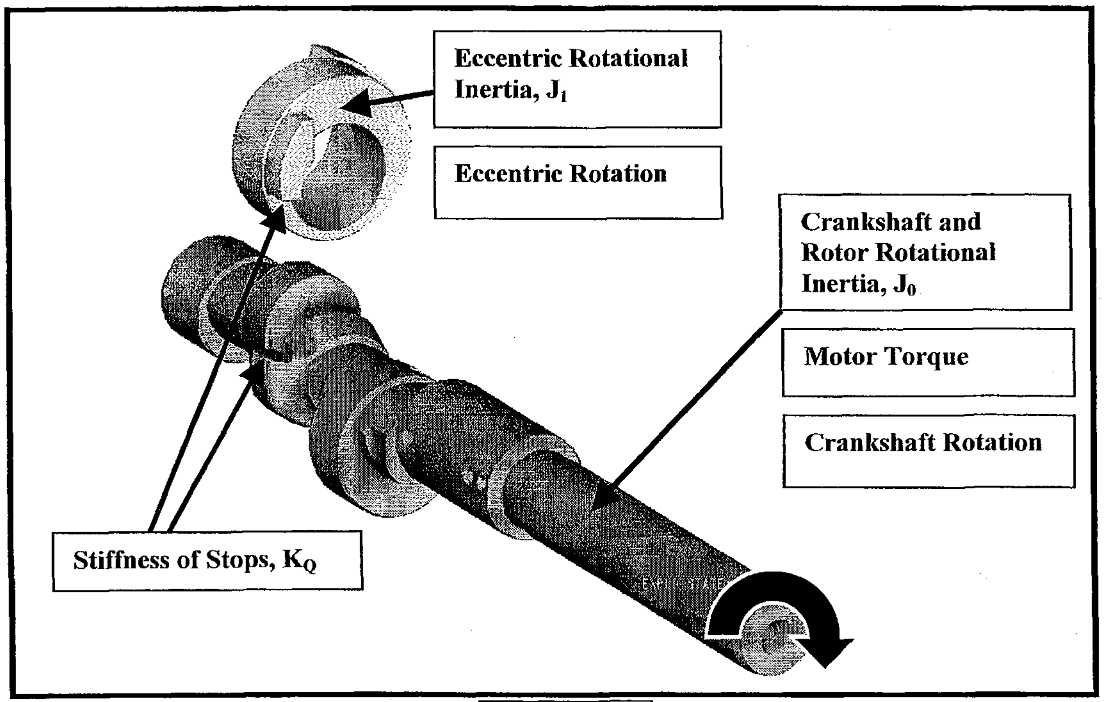


Figure 4

- Step 2: Transfer differential equations into block-diagram format inside of commercial simulation software. Figure 5 shows a piece of a typical block diagram where blocks represent functions to be performed on the input. In this case, integration blocks numerically integrate the crankshaft acceleration, $\ddot{\Theta}$, to give crankshaft velocity, $\dot{\Theta}$, and then crankshaft position, Θ. Figure 6 shows the block diagram of the entire system.

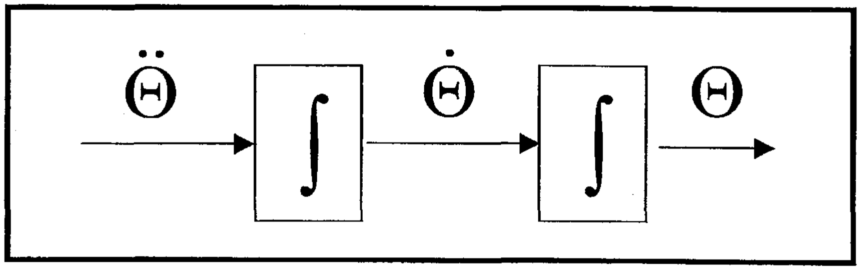


Figure 5

- Step 3: Use the simulation software to solve the equations, and generate output as needed. In this special case of very stiff parts colliding at high velocity, care must be taken to select the proper time increment with which to integrate the equations, otherwise the phenomenon will be missed. It was found that a time step of 10μ-seconds was adequate.

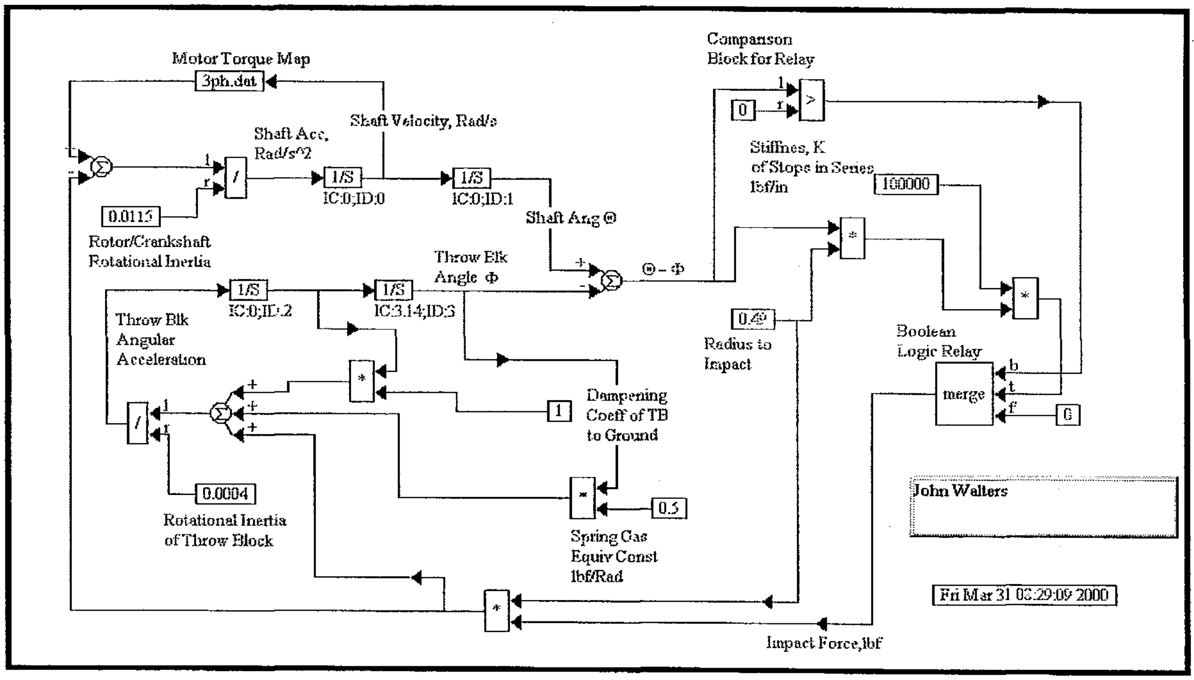


Figure 6

NOMENCLATURE EXPLANATION

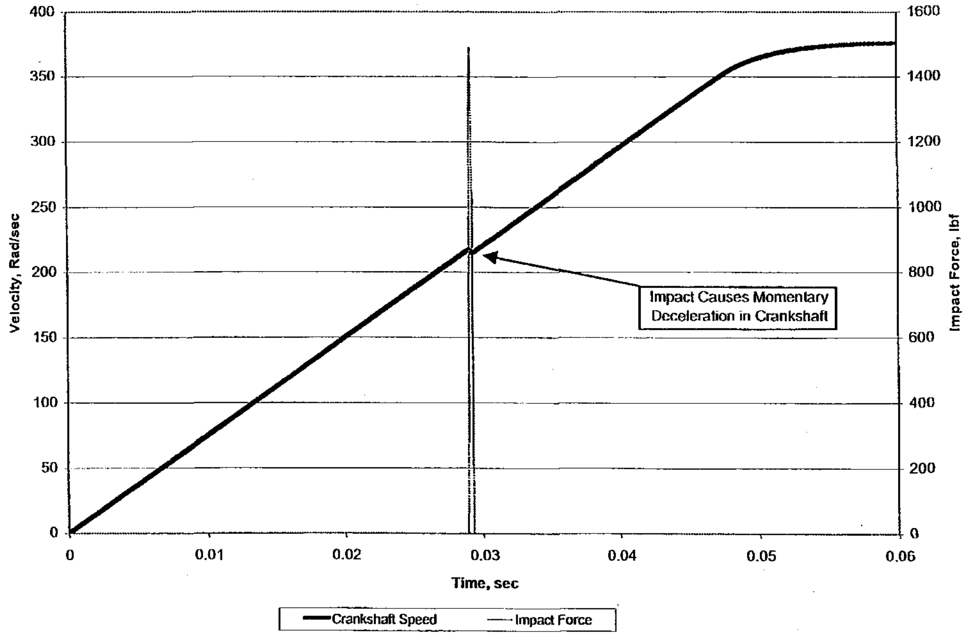
$\Theta,\dot{\Theta},\ddot{\Theta}$	Crankshaft angle, velocity, acceleration
$T(\dot{\Theta})$	Torque of motor, input as a function of speed
J_o	Rotational inertia of crankshaft and rotor assembly about crankshaft centerline
K_Q	Equivalent linear spring constant (Part Stiffness) at stops, evaluated by FEA model
r	Radial distance from centerline of crankshaft to contact point on eccentric
J_1	Rotational inertia of eccentric and piston/rod assembly about crankshaft pin centerline
Φ	Angular position of throw block with the same zero reference as Θ. It can be given an initial value Φ_o to represent an offset between the crankshaft stop and the eccentric during start-up
K_{t2}	Equivalent torsional spring from compressing refrigerant, can be used accurately over small crank angles
C_{t1}	Equivalent torsional damper proportional to relative velocity between eccentric and crankshaft, Models Impact Dampening from effects such as oil film.
C_{t2}	Equivalent torsional damper proportional to relative velocity between eccentric and ground

RESULTS

Figure 7 shows an output graph of the impact force and crankshaft velocity versus time for an intermediate design. The rapidity of the phenomenon is evident – the impact has begun and terminated in 600 μ-seconds. Figure 7 also illustrates the shock imparted to the relatively massive crankshaft. It can be seen that the crankshaft is subjected to a severe deceleration when the impact with the eccentric occurs.

Figure 7

Simulation Output: Impact Force and Crankshaft Velocity at Start-up



Once the simulation model was built, it was used as a design tool. The effect of critical system variables on the impact force can be studied. Figure 8 shows a graph of impact force versus eccentric rotational inertia. Figure 9 shows a graph of impact force versus crankshaft/rotor rotational inertia. An increase in crankshaft/rotor rotational inertia will decrease the velocity at impact, and therefore decrease the peak impact force in the mating parts. Sensitivity studies such as these allowed us to accept or reject proposed design changes without building prototype parts and performing testing.

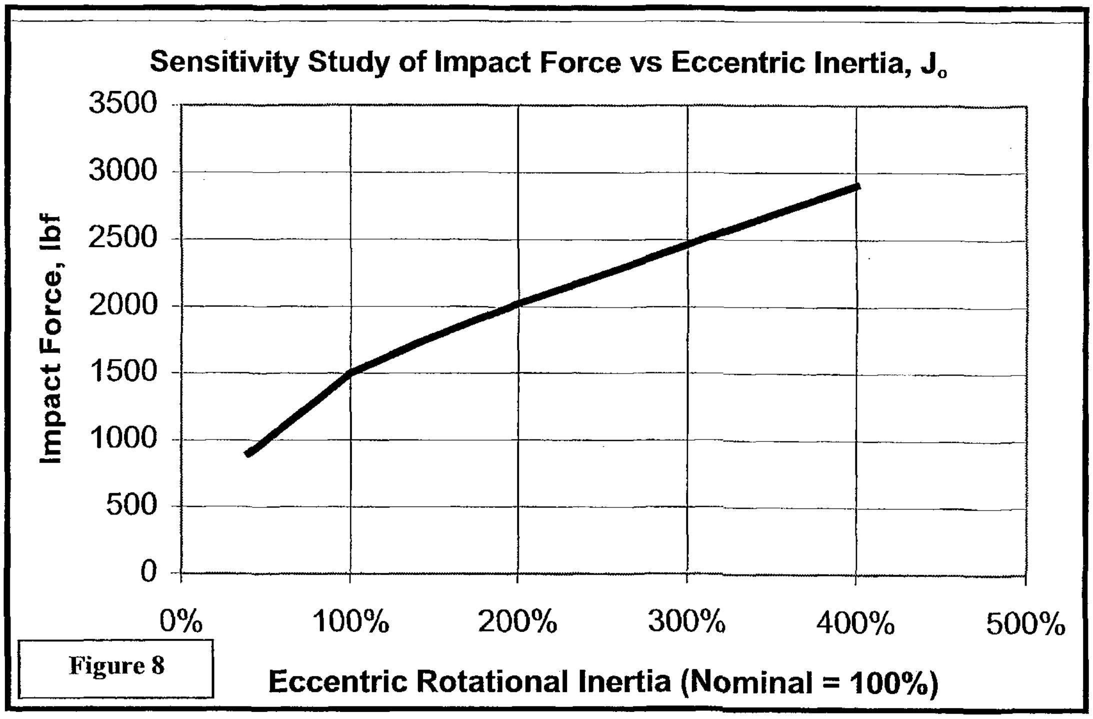


Figure 8

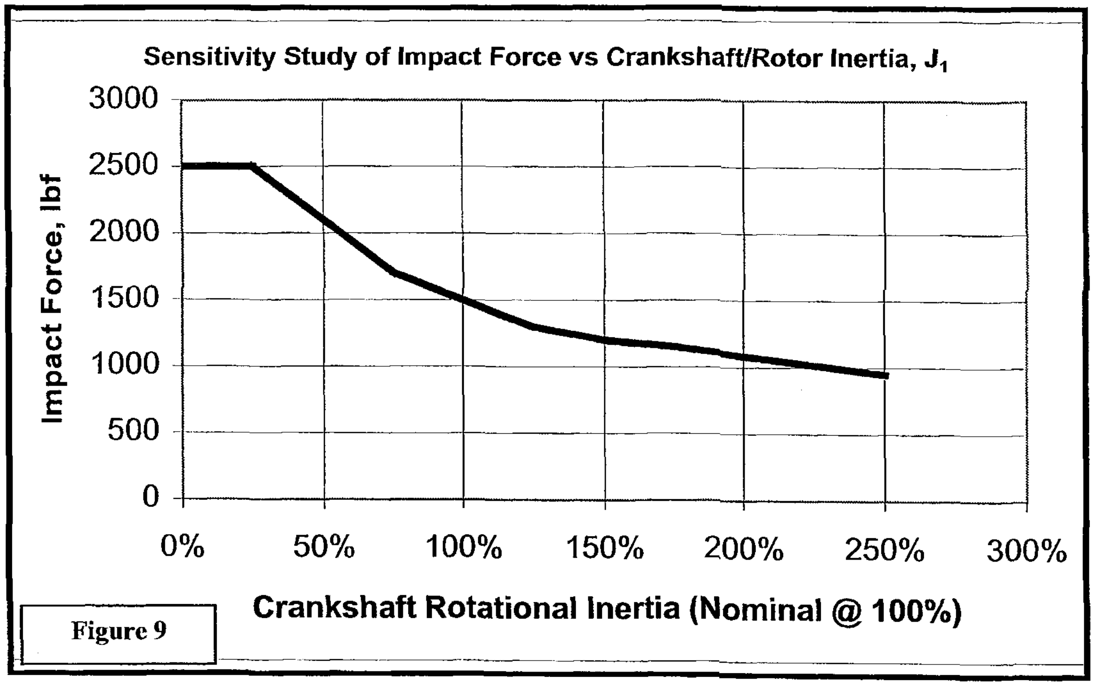


Figure 9

CONCLUSIONS

While designing the eccentric mechanism, this computational model served as a tool which allowed us to simulate designs and predict the impact loading that would occur. Also, the sensitivity of the impact load to changes in part mass, motor torque, etc., could be studied. Using this computational model allowed us to accept or reject proposed design changes without time-consuming prototype testing. The number of prototype cycles was minimized, and the result of this design process was a robust and functional design.