902048

Development of the Handheld Low Voltage Electromagnetic Riveter

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ABSTRACT

The Handheld Low Voltage Electromagnetic Riveter (HHER) has been under development for the past three years. The HHER is an impulse device deriving its power from the discharge of a bank of capacitors through a pancake coil. This gives the HHER the advantage of an accurate and repeatable output force, which results in exceptional consistency in rivet upset dimensions. The rivet/hole interferences obtainable with the HHER have been shown in many cases to be superior to traditional rivet driving techniques, resulting in riveted joints that exhibit excellent fatigue life.(5)

Typically, two opposing guns are used on either side of the rivet. These are synchronized through a control cable of arbitrary length. This feature allows accurate installation of slug rivets by hand, a function that in many cases is not possible with existing handheld tools. For the case of headed rivets, the force balancing bias feature eliminates of the cosmetically undesirable “salt and pepper” marks which are characteristic of pneumatic riveters.

In addition to improved rivet quality for the manufacturer, the HHER systems offer the operator advantages as well. The HHER is extremely quiet operating many decibels (typically under 90 dB peak) below that of pneumatic rivet guns. In many cases no ear protection is necessary. The one shot formation results in a decrease in formation time for tough fasteners such as A286 and large diameter solid aluminum rivets, reducing worker fatigue.

Electroimpact has worked closely with many aerospace companies in the advancement of the HHER designs. This work has resulted in four different models with increasing capacity. Two models are currently being used in production at two aerospace companies.

INTRODUCTION

During the past three years, there has been a growing interest in and implementation of electromagnetic riveting systems. This has primarily been a result of the introduction of the Low Voltage Electromagnetic Riveter (LVER) technology at FASTEC'86 (1). These systems offer a number of advantages over conventional systems, which can significantly increase production and improve the factory environment. Hand in hand with the development of the LVER technology has been the development of the handheld LVER systems. These hand-operated systems provide a controllable and repetitive method of installing of aircraft fasteners.

A number of different configurations of the HHER address various needs in the aerospace industry. The current units range from an 8 lb. actuator capable of installing up to 50 3/16" rivets per minute to a 180 lb actuator capable of installing up to 10 3/8" rivets per minute. Weight, output capacity, ease of operation and safety are the principal design criteria for all these units.

THEORETICAL DESIGN PARAMETERS

LVER technology is based on eddy current repulsion between a copper pancake coil and a copper driver plate. Two actuators are typically employed on opposing sides of the rivet. Each actuator is connected to its own capacitor bank by a coaxial pulse cable. After the capacitors have been charged to a predetermined voltage, this stored energy is discharged through the coil. An intense magnetic pressure quickly develops between the coil and the driver plate, accelerating the driver into the rivet. Peak forces of over 30,000 lbs can be reliably and accurately generated using this technology.

The basic system consists of two actuators, two capacitor banks and a control box as shown in Figure 1. Each actuator is connected to a capacitor box by a coaxial pulse cable and a small control cable. These cables are typically 12-15 ft. in length. Each capacitor bank is connected to a control box by a small diameter control cable of arbitrary length. This allows the actuators to be used on large aircraft structures.

The primary design concerns of handheld LVER systems are the peak output force needed to form the specified fastener and the amount of recoil felt by the operator. From the standpoint of a handheld device, we seek to maximize the relationship of Output Force/Recoil Force while minimizing the weight of the actuator.

The force output of LVER machines is in the form of a narrow high intensity impulse resulting in only a small amount of momentum being transferred to the operator. The magnitude of the LVER output force is dependent upon the area of the electromagnetic coil, system capacitance, cable impedance, capacitor bank voltage and the amount of recoil mass. The exact relationship between these parameters is beyond the scope of this paper, for a more in depth analysis, see Zieve (4). It is important to understand two basic concepts. 1) A decrease in the duration of the force pulse results in less momentum, i.e. lower recoil force. 2) A certain minimum amount of recoil mass is necessary to achieve the desire output force.

Older electromagnetic riveting systems minimized the duration of the force pulse by using a small amount of capacitance and high voltage (2), (3). Typically, these systems operated at voltages between 5,000-10,000 volts, making them inherently dangerous. The force pulse rise time of these high voltage systems was too fast. This fast rise time results in a high strain rate in larger rivets, which caused microcracks under the formed heads. (6) LVER technology uses a combination of high capacitance and low operating voltages. Typically, operating voltages of LVER machines are under 500 VDC. The larger amount of capacitance and variations in the coil geometry increase the system time constant, slowing the output force pulse and eliminating the rivet microcracks. (6)

The magnitude of the recoil mass effects both the peak output force and the amount of recoil felt by the operator. The transfer of electromagnetic energy between the coil and the copper driver plate is effective only over a small distance. In order to maximize the output force, it is important to keep this gap to a minimum during the formation of the rivet. This is accomplished by having a sufficient amount of inertia behind the coil such that the coil movement during the rivet formation is negligible. The amount of mass required is dependent upon the force output of the driver. Figure 2 illustrates this relationship. Peak force measurements were taken using a piezoelectric crystal during the formation of a 3/16" diameter 7050 aluminum rivet. A peak force of approximately 5500 lbs is required for this application. This curve illustrates the dramatic effect of recoil mass at low values. This can be compensated for to a certain extent by increasing the system voltage, however it is desirable to keep the voltage as low as possible for a particular application. For greater output forces the curve becomes steeper at lower masses and the flat portion of the curve shifts to the right.

The amount of recoil mass also affects the magnitude of the peak force felt by the operator. A larger recoil mass allows more energy to be stored in the inertia of the system. This results in lower peak recoil acceleration and consequently a lower peak force felt by the operator. However, to keep the actuators portable, it is also desirable to minimize the actuators weight. This is accomplished by using an internal recoil absorption system. When the actuator is fired, the coil and recoil mass slide internally compressing a cylinder of shock absorbing foam of various densities. The internal recoil stroke stretches out the recoil pulse and minimizes the peak acceleration felt by the operator, i.e. a large amount of the recoil energy is absorbed internally by the foam. This concept is illustrated in Figure 3. Plate 1 shows an actual HH100 internal recoil system.

For the smaller actuators, the amount of recoil weight is determined solely by that required to achieve the desired output force. This keeps the actuator weight to a minimum. The recoil force increases with the output force. Therefore, more recoil absorption is required at larger output force to maintain the recoil at a tolerable level. This can be accomplished by increasing the internal recoil stroke length. Internal recoil systems in conjunction with a minimum amount of recoil mass work well for the formation of rivets up to 1/4” in diameter. Above this, the increased length of the required recoil stroke becomes impractical at the minimum recoil mass. For larger fasteners, reduction in the recoil force therefore becomes the dominating factor in choosing the amount of recoil mass. Addition of more mass with or without some shock absorbing foam is very effective at reducing the peak recoil acceleration, thus keeping the recoil felt by the operator at a comfortable level. It does imply however that for the larger fasteners these systems must be counterbalanced.

The operational design criteria of the LVER based handheld system are summarized in Table 1.

OPERATING SAFETY

The low operating voltage of the LVER handheld tools make them inherently safer than their high voltage predecessors. Nevertheless, many safety features have been included to protect the operator. The actuators are constructed from high strength non-conducting nylon and polyurethane. The drivers and front bearings are electrically grounded, ensuring that the operator is electrically isolated at all times. The electrical system in equipped with a sensitive ground fault detection switch and interrupt. Should ground fault occur in the gun, cable or capacitor bank, the system automatically shuts down and dumps all charge in the capacitor banks through an internal resistor.

Accidental discharge is prevented by a spring that opens up a gap between the electromagnetic coil and the driver. When this gap is as little as 1/2” the force transferred to the driver from accidental triggering is negligible. The operator must therefore physically compress this spring by bringing the driver in contact with the work piece to transmit any appreciable force from the coil to the driver.

ADVANTAGES OF LVER HANDHELDS OVER CONVENTIONAL TOOLS

LVER hand operated tools offer many advantages over the conventional hand installation methods both to the operator and the manufacturer. For years the only method of installing rivets by hand in most situations has been using a pneumatic percussion hammer on one side and a bucking bar on the opposing side. There are a number of problems with this method of installation, however until now there have been no alternatives. The LVER handheld systems give manufactures an alternative.

1. Rivet Quality: The electronic nature of LVER technology gives the manufacturer a highly controllable means of installing fasteners by hand. One of the biggest problems with pneumatic riveting is the large scatter in the quality of the installed fasteners. This is largely dependent upon the operator. Experienced operators install rivets by a sense of “feel”. The end product is accepted or rejected by gages and flushness measurements. Yet, these gages do not always reveal the true quality of the rivet. The quality is determined by a controllable, repetitive process,

and with pneumatic systems there is too much room for variation. Hand installed LVER rivets are highly controllable. The capacitor voltage and force balancing bias are set electronically at the control box. The optimum settings can be predefined and preset by the manufacturing engineer. By the time the LVER system reaches the shop floor the engineer can be assured that the result will be highly repeatable from shot to shot.

2. Worker Fatigue: The size of pneumatic hammers and bucking bars increase with the rivet size. Nevertheless, with the largest rivets it still can take over a minute of continuous pounding to install these fasteners. It requires a great deal of strength and stamina to knock down these large fasteners resulting in excessive worker fatigue, a significant drop in productivity and a reduction in the quality of the installed fastener. Some companies have accepted the fact that these large fasteners cannot be installed acceptably by hand and therefore have added another operation (cold working of the holes) or have gone to two piece fasteners to ensure the correct compression levels are reached in the holes. This results in loss of time and money.

Some companies have introduced slight solutions to the worker fatigue problems. Damped vibratory hammers or rubber handled bucking bars have been offered as a solution. But these solutions only serve to Band-Aid the problem. The piercing sound of the pneumatic riveting gun is common to all aerospace assembly plants. This noise is very irritating and even with protective ear wear it is a large contributor to fatigue. The decibel levels during the installation of large fasteners can reach as high as 140 dB. At this level even ear protection does not help and the noise level can directly effect not only hearing but also the body's nervous system.(7) All these factors lead to a significant decrease in the morale of the shop floor workers. Many can only work for limited time at these high noise and vibrational levels causing a high turnover rate and a loss in productivity and quality.

LVER systems operate at a much lower decibel range. In many cases, no ear protection is necessary. This is due to the lack of repetition and the absence of a pneumatic pressure release. The size of the LVER handheld tools increase as do their pneumatic counterparts with the size of the fastener. The larger the coil area and the larger the recoil mass the greater the amount of output force possible with LVER tools. For a given actuator however the riveting force can be arbitrarily adjusted downward by reducing the voltage, only the maximum force is limited by the actuator capacity. Proper sizing of the actuator to the job function and use of an ergonomically designed handle make these units comfortable to operate.

3. Slug Rivets: Forming slug rivets into countersunk holes is a common practice on aerodynamic structures such as wings skins. Installing slug rivets in straight holes is common practice in parts such as spars. These operations are not possible except in limited cases to perform with conventional hand tools, since there is no effective means for setting the protrusion height. In many cases where hand installation is required, manufacturers must use bolts which are significantly more expensive

both in part cost and in hole preparation. With the LVER hand installation of slug rivets becomes possible. The rivet height is set prior to firing by an adjustable hard stop on the nose of one of the actuators. The other gun pushes the rivet against the opposing ram and the correct position is set. When the guns are discharged, the synchronize pulses form the rivet equally from both sides, keeping the rivet in its preset position.

Cycle rate is always of main concern when considering production speed. LVER handheld riveters are capable of installing up to 50 3/16" rivets a minute. This rate is slightly lower for larger fasteners and higher for smaller fasteners. When operated at this rate continuously, the coils must be cooled. As energy is discharged through the coil, resistive heating causes the coil temperature to rise. The coils are cooled by blowing filtered shop air directly through the windings. In order to overcome the variations in the transient "warm up" period, the power supply can be made to automatically compensate the voltage setting to make up for the variation due to the rise in the coil's temperature. With this feature, consistent LVER performance can be maintain within 1% during operation.

The electronic nature of the LVER technology allows not only precise control of the riveting process but also allow precise monitoring of the process. The output pulse of the capacitor banks can be recorded in a computer data bank and used for quality control of the fastener installation. This type of process control can greatly improve the quality of the product as well as decrease the amount of inspection time.

DESIGN RESULTS

1. Initial Stages: The very first LVER handheld system had the capacitor banks built directly into the actuators. This configuration eliminated the resistive and inductive losses in the pulse cable and the need for a separate box for the capacitor banks. Plate 2 shows this initial prototype. The result was a 17 lb actuator that was capable of forming 3/16" diameter fasteners. A pilot program was launched in 1986 to get Industry feedback on this configuration. Industry's main concern with this configuration was that it was too heavy and bulky when compared to the alternative hand tools.

The next stage was the development of a smaller actuator that was similar in configuration to the traditional riveting guns. This was accomplished by housing the capacitors in a separate enclosure and connecting these to the actuators by a pulse cable. In order to reduce the inductive losses in the cable, which can be substantial at the currents involved, a coaxial pulse cable was developed. Each capacitor bank was connected to a single control box that housed all the controls of the system. The system was powered through a 11 0VAC/1 5A conventional wall socket. This unit was able to achieved cycle rates of approximately 12 rivets a minute.

This system was received by Industry with greater interest. These initial actuators were configured as many hand tools are with a pistol grip handle containing the trigger assembly and an auxiliary handle that allows stabilization of the tool. Although the axial magnitude of the recoil was not significant, the off center position of the pistol grip handle resulted in a torque applied the operators wrist. The handle was then moved to the back of the unit on line with the axial motion of the recoil. The handle is ergonomically designed at the optimum wrist angle to eliminate any torquing of the wrist during the recoil stroke and foam padded to further protect the operator.

2. HH100: The current HH100 system consists of two 8 lb actuators, each connected to a 25 lb capacitors bank. The heart of the system is a 2.25” diameter electromagnetic coil. This system has sufficient power to upset 3/16” solid aluminum fasteners. An internal shock absorption system is used that allows the coil to recoil into shock absorbing foam. This reduces the peak recoil force to a comfortable level. An LED located on top of the gun is activated by the trigger of the opposing gun and serves as a communication device between the two operators. The guns will not fire until both of these triggers are pressed. A second LED is used to indicate the status of the capacitor banks in reference to the prespecified charge voltage.

By increasing the power input to standard factory power of 440V/3 PH, these units can install up to 50 rivets a minute. The input power is only seen at the control box, which can be located up to 250 ft away from the actuators. Plate 3 shows this HH100 system.

3. HH300: The next step in LVER handheld technology was the development of a handheld unit capable of installing up to 1/4” diameter fasteners. For the reasons described above this required a larger diameter coil, more capacitance and greater amount of recoil weight. The weight of the unit was kept to a minimum to enable it to be used without a tool balancing system. The HH300 is designed around a 2.88” diameter coil. The resulting actuator weighs 17 lbs. The stroke of the internal recoil system and the recoil mass were both increased over the HH1 00 to reduce the recoil force. Plate 4 shows the HH300 actuator. At 17 lbs., the unit is still light enough to be used intermittently without a tool balancer. However, in high cycle rate production work a means for offsetting the actuator weight is required.

These units were developed for Textron Aerostructures to aid in the qualification of the LVER process. The units were qualified and are currently in production at Textron. These are being used for installing 3/16” and 1/4” slug rivets in 7150 aluminum J-stringer to skin joints. Some of the qualification results were presented at the FASTEC ‘89 conference (see Hartmann [5]).

It was found that for the long 1/4” rivets the recoil was larger than was desired. To reduce the recoil without significantly affecting the actuator weight would require increasing the recoil stroke beyond a practical length. The unit would become bulky and difficult to operate. The other option was to add mass to the system and eliminate the internal recoil system. It was decided that since the units use a tool balancer in production at 17 lb., additional weight would not pose significant problem.

4. HH400: Testing was performed to determine the required actuator weight to reduce the excessive recoil of the HH300 system. The elimination of the internal system allows the entire actuator weight to be used to absorb the recoil energy. Increasing the actuator weight to 75 lbs reduced the recoil felt by the operator to minimal level. At this weight a tool balancing system is required. A sliding attachment bracket is located on the top of the actuator to allow the attachment point to be fixtured above the center of gravity allowing the actuator to be easily positioned.

The HH400 can either use a 2.88” diameter coil as used in the HH300 or a 3.25” coil. It has the capacity to upset 1/4” A286 rivets and even some softer, 2117, 5/16” diameter rivets. Even at these high output forces the HH400 remains comfortable to operate. Plate 5 shows the HH400 actuator.

5. HH500: The installation of very large rivets such as 3/8” 7050 aluminum fasteners presents quite a challenge even for large hydraulic presses. Over 30,000 lbs of force is required to form these types of rivets. Many companies have elected against using these large rivets and instead have chosen to use two-piece fasteners because of the problems involved in rivet installation. These large rivets can be installed by hand but it requires a 9X pneumatic rivet gun and a very heavy bucking bar. The high noise and vibrational levels experienced during the installation of these fasteners leads to excessive operator health problems and low morale.

The next step in LVER hand tool development was the design of a hand operated system capable of installing these large fasteners, the HH500. The HH500 system offers a means of cutting the installation time of these large fasteners. Plate 6 shows the HH500 actuator. The significant reduction in vibration and noise levels creates a healthier working environment. The HH500 is constructed around a 3.75” diameter electromagnetic coil. In order to minimize the recoil force, the weight of the HH500 was increased to 180 lbs. These units put unprecedented power into the hands of the operator with a force generating capacity of over 30,000 lbs. Powered by 440V/ 3PH, this unit can install up to 10 3/8” rivets a minute, vs nearly 90 seconds each for pneumatic riveters. This unit is currently undergoing qualification at two major aerospace companies.

HHER TOOLING CONSIDERATIONS

Tooling plays an important role in all riveting processes. Plate 7 illustrates the various type of tooling available with LVER’s hand units. The rivet formation dynamics of LVER technology is significantly different from those of conventional processes. With LVER, the rivet’s strain rate of the formation is higher than during either pneumatic or hydraulic riveting, due to faster rise time of the electromagnetic pulse.

1. Die Geometry: Typically with conventional processes, a flat or shallow oval shaped die is used. These dies do not work well with electromagnetic riveting for most applications. To achieve acceptable “hold fill” with the LVER technology, the rivet must be contained radially and driven down into the hole. This is accomplished by using cup dies. The die geometry is based on the volume of the protruding rivet tail,

the minor diameter of the rivet and the required bucktail diameter. Slight variations of die geometry are made based on results from interference measurements and the fatigue performance of representative tests. This is an exacting, empirical process that usually requires a number of iterations to achieve the optimal results. Each application adds a unique feature that may require some alteration to the exact geometry. In all cases to date, when this procedure is followed, the end result has been a formed rivet that at least meets existing specifications and in many time exceeds them. The main concern that seems to always come up with manufactures who are unfamiliar with this process is the cosmetic appearance of the cupped heads. All studies known to the author have clearly illustrated that the cupped head offers no adverse effects to the riveted joint in either fatigue, shear or tensile strength.

2. Die Centering: Centering the die on the rivet is a trivial task for most CNC type of riveters. This is not the case however with handheld tools. Since the LVER is a one shot device, there is little margin for error. All handheld cupped dies are designed such that the minor die diameter closely matches the diameter of the rivet. This insures that the rivet is centered on the die prior to firing. There are cases however where a flat surfaces die is appropriate, such as with index head and some type of protruding head rivets. Attempting to center a small diameter flat on a rivet of the same diameter or on a rounded surface is not an easy operation. To overcome this problem a polyurethane centering sleeve is used. This sleeve retains the rivet allowing exact centering. When the rivet is formed, the die moves forward expanding the polyurethane out of the way.

3. Ram Tooling: Three different tooling configurations are used with LVER hand guns. For the smaller units, the drivers accept standard .401" diameter tooling used with pneumatic riveting guns. This allows the use of standard tooling, where appropriate, which is available at all aircraft manufacturing plants The driver is bored to a diameter closely matching the .401" diameter of the tooling and then is fitted with an internal 0-ring to retain the dies. On lower force machines the friction between the 0-ring and the die are sufficient to retain the dies.

For the higher force machines, HH300 and above, threaded tooling is employed. It was determined that 0-rings were unable to retain the die well enough considering how the tools may be abused on the factory floor. Both externally threaded and internally tapped dies are used depending on the application. The size of the threaded section is somewhat dependent upon the size of the rivet and the side clearances available.

4. Offset Riveting: Riveting around obstructions, i.e. offset riveting, comes up quite often in the aircraft assembly. Due to the high speed of formation, the offset rams used with electromagnetic riveting must be dynamically balanced. If a common offset ram is used the dynamic loads due to the off-center mass creates a large bending moment on the ram shaft shifting the rivet to one side. Dynamically balanced rams eliminate this problem. Plate 7 shows a typical

dynamically balanced ram and driver.

FUTURE DEVELOPMENT

Work continues on reducing the weight of the smaller actuators to more closely match that of existing pneumatic riveters. The HH100 could easily be downsized to 3-5 lbs if limited to 5/32” diameter rivets. Most manufacturers however seem to desire a unit that has the capacity to install at least 3/16” diameter fasteners. There may indeed be a way to achieve this by using an innovative coil configuration. Some progress has been made in this area over the past year although it is not yet at the stage of factory implementation.

CONCLUSIONS

The development of LVER handheld technology has progressed a great deal since its inception in 1986. Feedback from Industry and trials on the factory floor have lead to a number of different actuator designs and enhancements. These units give manufacturers an alternative to the conventional pneumatic riveters, allowing operations that are not possible with conventional hand operated tools such as the installation of slug rivets. The low noise levels and lack of vibration of the LVER systems help to create a better working environment and reduce worker fatigue. This leads to higher productively and cost savings.

References

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3. US Patent 3646791, Leftheris, 11/70
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7. OSHA, “1910.95-Occupational Noise Exposure”

Table 1: Design Parameter Summary

Increase the....	Operator Recoil	Force Output
1. Amount of Capacitance	Increases	Increases
2. Cable Impedance	Decreases	Decreases
3. Capacitor Bank Voltage	Increases	Increases
4. Driver Weight	Decreases	Decreases
5. Recoil Mass	Increases	Decreases
6. Internal Recoil Stroke	Unaffected	Decreases
7. Electromagnetic Coil Area	Increases	Increases

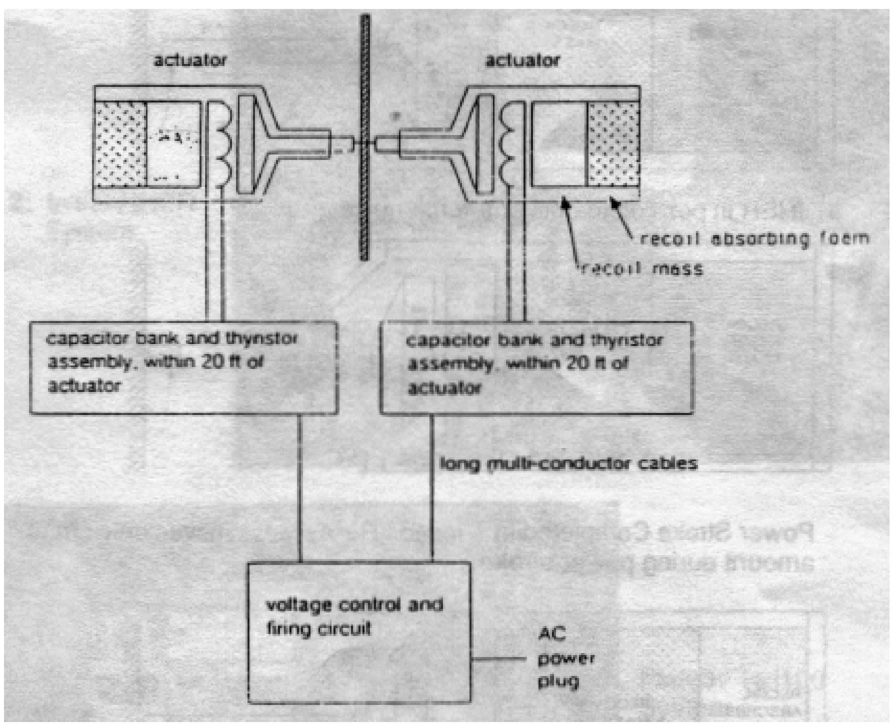
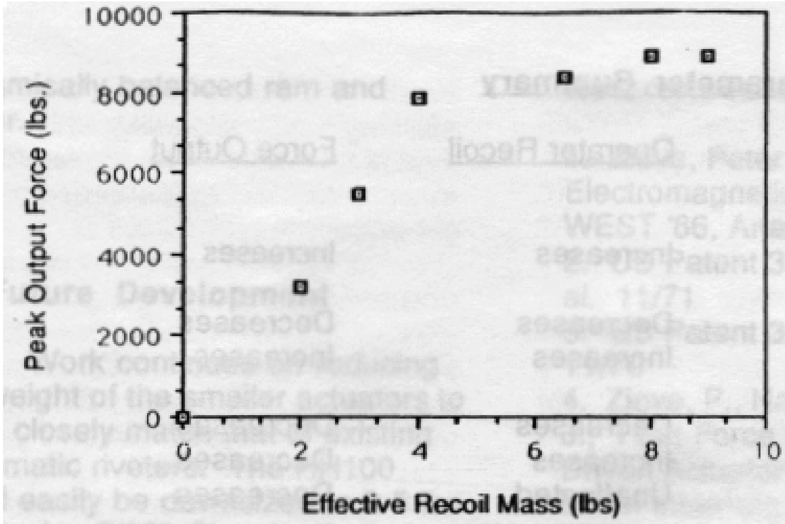
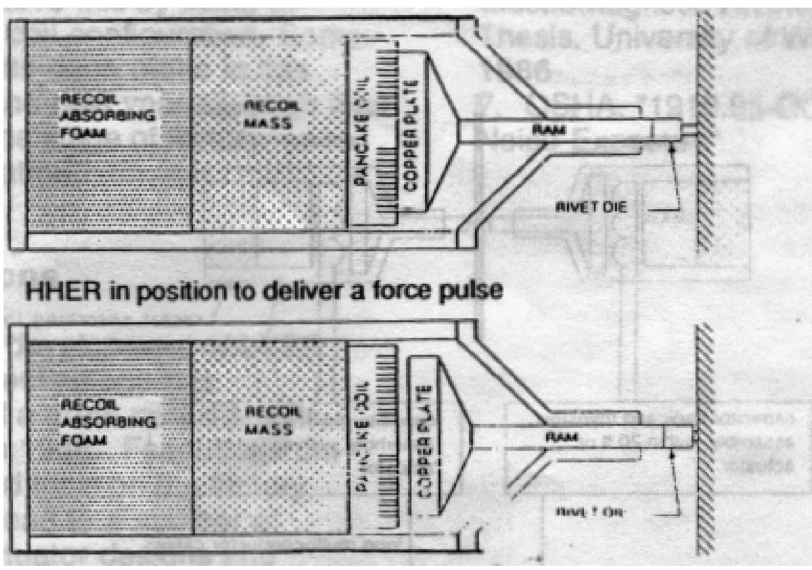


Figure 1: Typical LVER System Block Diagram

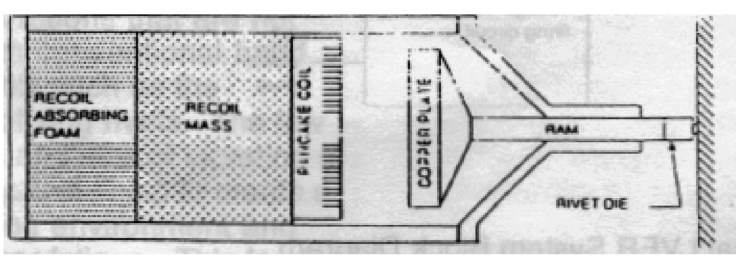


2.5k diameter coil, 4 capacitors. 12 ft pulse cable, 340V discharge

Figure 2: Relationship Between Recoil Mass and Output Force



Power Stroke Completed in 1 msec. Recoil Mass moves only small amount during power stroke

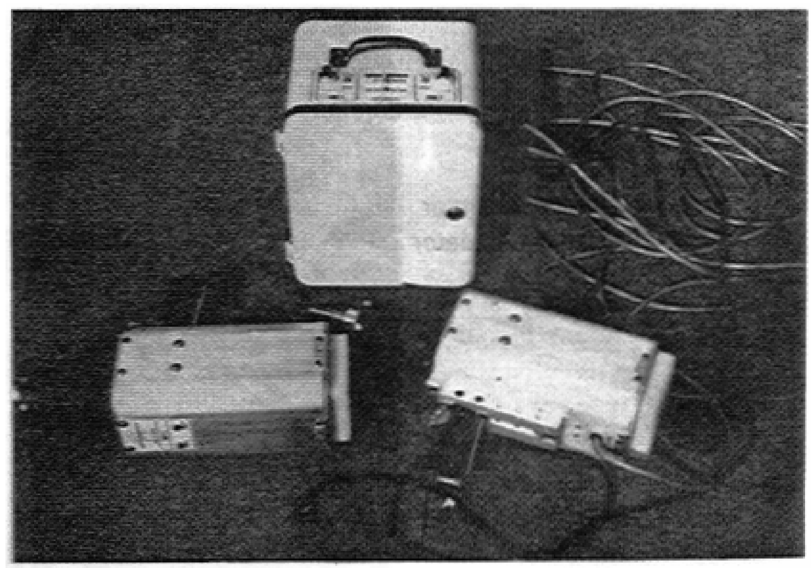


Recoil Mass is decelerated to a stop in approximately 100 msec.

Figure 3: Operating Sequence of Internal Recoil System

Plate 1: Internal
Recoil System
HH100

Plate 2:Initial
HHER System



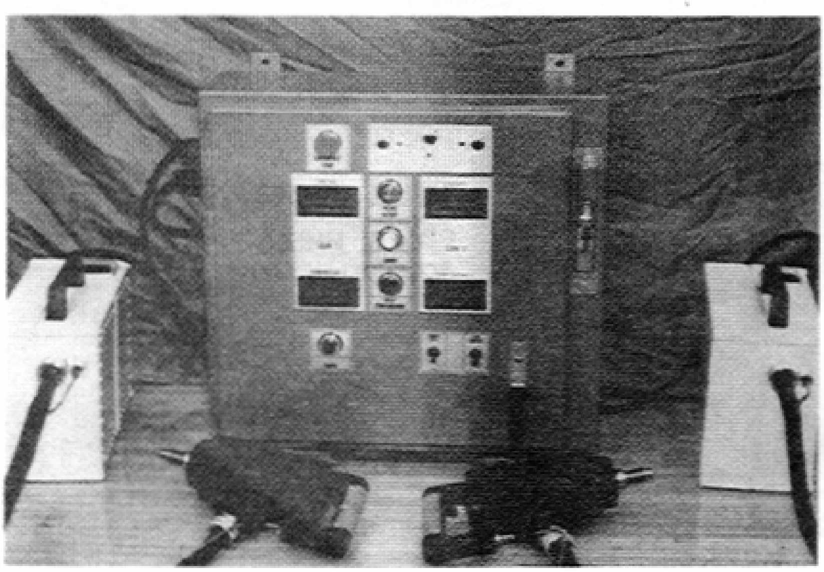


Plate3: HH100
System

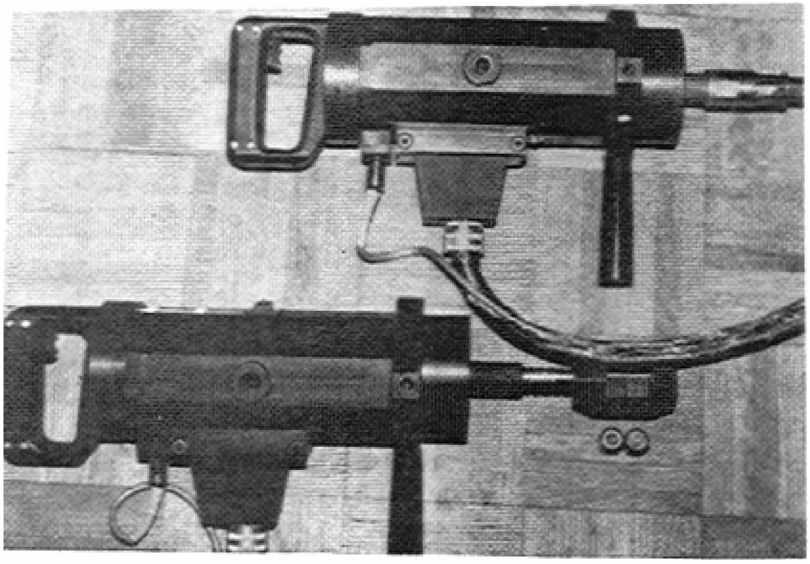


Plate 4: HH300
Acutators

Plate 5: HH400
Actuator

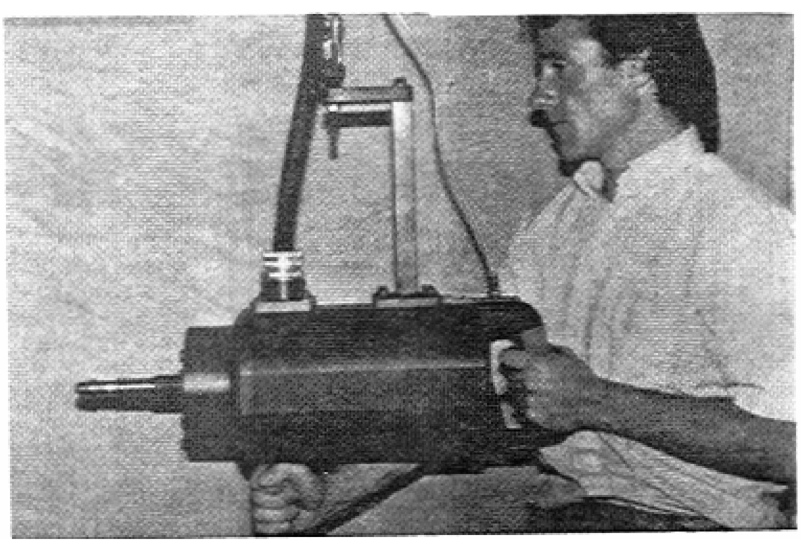


Plate 6: HH500 Actuator

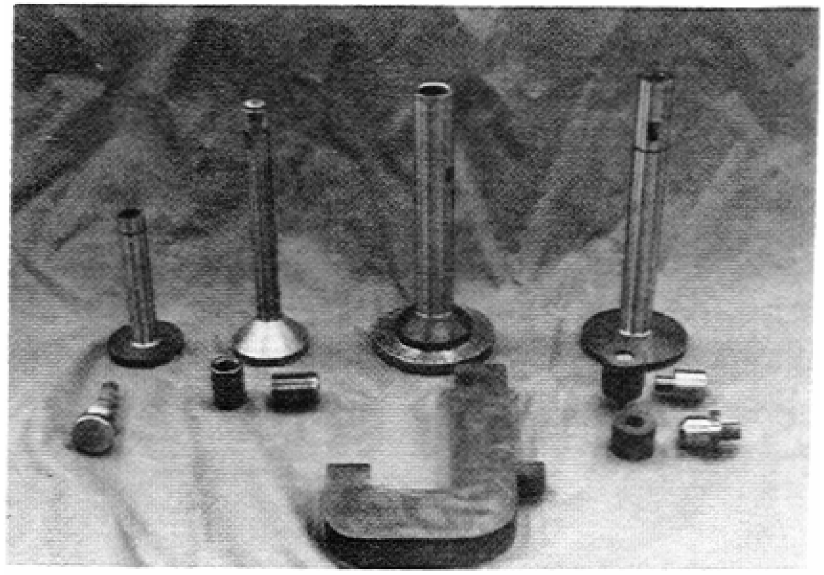


Plate 7: HHER Tooling

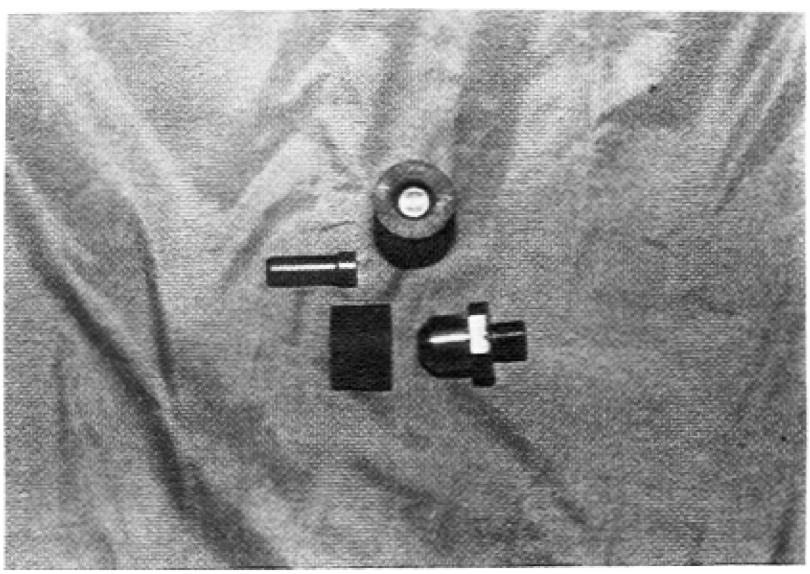


Plate 8: Index/Universal Head Self Centering Tooling