Design of Pulsed Coil-Guns

S. Williamson and C.D. Horne
University of Cambridge, Department of Engineering, Trumpington Street,
Cambridge CB2 1PZ, U.K.

D.C. Haugh,
Defence Research Agency, Fort Halstead, Sevenoaks, Kent. TN14 7BP, U.K.

Abstract - **The paper describes a two-step procedure for designing pulsed coil guns to suit a given power supply. The stator is designed coil-by-coil using an overlapped optimisation procedure that takes account of inter-coil coupling. The armature is designed by notionally removing material from an oversize blank on the basis of a utility factor calculated from the local force distribution.**

I. Introduction

Methods for pulsed coil-gun analysis are relatively well developed, with both coupled-circuit [1]-[3] and finite-element models having been described in the literature [4] - [6]. Coil-gun synthesis, on the other hand presents a completely different picture. There are no practical step-by-step procedures that lead directly from a set of design objectives and constraints to a design that meets these criteria and which is in some sense optimal. Design of coil-guns is largely a matter of extrapolation from previous experience, along with trial-and-error modifications. In this paper the authors propose a formal procedure for coil-gun design in two steps. The first step employs formal optimisation procedures to choose leading design parameters, and effectively fixes the stator design. The second step involves re-designing the armature, allowing shape as well as dimensions to change, in order to improve overall performance.

II. Experimental Verification of Analytical Model

The work contained in this paper requires the repeated use of a performance analysis code, and it is appropriate, therefore, to begin by verifying that code against experimental results. The model used in the code employs the coupled-circuit approach, which has been extensively described in the literature, although experimental confirmation is less common. The Cambridge experimental facility consists of a four-stage coil-gun, using an ignitron-switched 25 kJ capacitor to energise each stage. The stator has four identical 42-turn coils, with an inside diameter of 66.5 mm. The projectile used in the experiments consists of a 200 grm copper ring mounted on a 300 grm polycarbonate sabot. Measured and computed coil voltage and current waveforms for each stage, during a four-stage launch are shown in Fig. 1. Experimental measurements of current were made using Rogowski coils, callibrated against a standard shunt. The temporal displacement between the waveforms for the second and subsequent coils arises because both the model and experimental gun use projectile position to trigger these stages. Any discrepancy between the projectile velocity in the real gun and that in the model will lead to differences between triggering instants in model and experiment. The important point, however, is that the shapes and magnitudes of the computed waveforms clearly mirror those obtained experimentally, giving confidence in the validity of the computer code.

Further evidence of validity is afforded by the close agreement obtained between measured and predicted muzzle velocity for single-stage, two-stage, three-stage, and four-stage launches, as shown in Table 1.

III. Stator Design

The authors propose that the stator of a coil-gun should be designed using formal optimisation procedures which seek to extremise an objective function of several variables. In the present context the objective function is the projectile velocity, and the variables are the design parameters. In essence, the optimisation routine varies the design in accordance with some algorithm in order to determine the combination that gives best performance. This is by no means a trivial problem, and there are many possible algorithms from which to choose [7]. The most efficient procedures employ algebraically-calculated derivatives of the objective function to choose a search direction. Unfortunately the derivative of exit velocity with respect to stator turns number, for example, is not available, and so the algorithm that is employed must estimate derivatives numerically using small perturbations. Each perturbation requires the coil-gun simulation program to be used to evaluate performance. This is a time-consuming procedure. The number of trial designs to be evaluated escalates rapidly with the number of stages in the gun. A single-stage

Manuscript received Feb 24, 1994.

S. Williamson, e-mail: sw @ eng. cam. ac. uk

TABLE 1

SUMMARY OF PREDICTED AND MEASURED RESULTS

Number of Stages	Velocity (ms^{-1})			Kinetic Energy (kJ)		
	Measured	Predicted	% error	Measured	Predicted	% error
1	96.2	96.4	+0.2	2.29	2.30	+0.5
2	150	145	-3.3	5.57	5.20	-7.1
3	172	171	-0.6	7.32	7.24	-1.1
4	211	204.4	-3.1	11.1	10.3	-7.2

launcher has seven parameters (three coil dimensions, three armature dimensions, and the coil turns number). Each subsequent stage in a multi-stage launcher adds five more parameters (two coil dimensions, inter-coil spacing, triggering instant, and coil turns number). A four-stage gun will therefore have 22 design parameters to be chosen, assuming of course, that the supplies have already been specified and the coil and armature materials are known. The rapid escalation of computing time is demonstrated in Table 2, which gives the time taken to optimise the designs of guns having different numbers of stages. These optimisations have been carried out on the assumption that the armature dimensions are fixed (by specification), that the stator bore is fixed by considerations of minimum clearance (maximum coupling), and that the inter-coil spacing is set to its minimum value (because experience has shown that this produces best performance). Such assumptions reduce the number of parameters to be chosen by the optimisation routine, thereby reducing the computing cost. In effect a coil array is being designed to suit a given armature and power supply. The times given relate to a modern powerful workstation (Sun SPARC centre 1000).

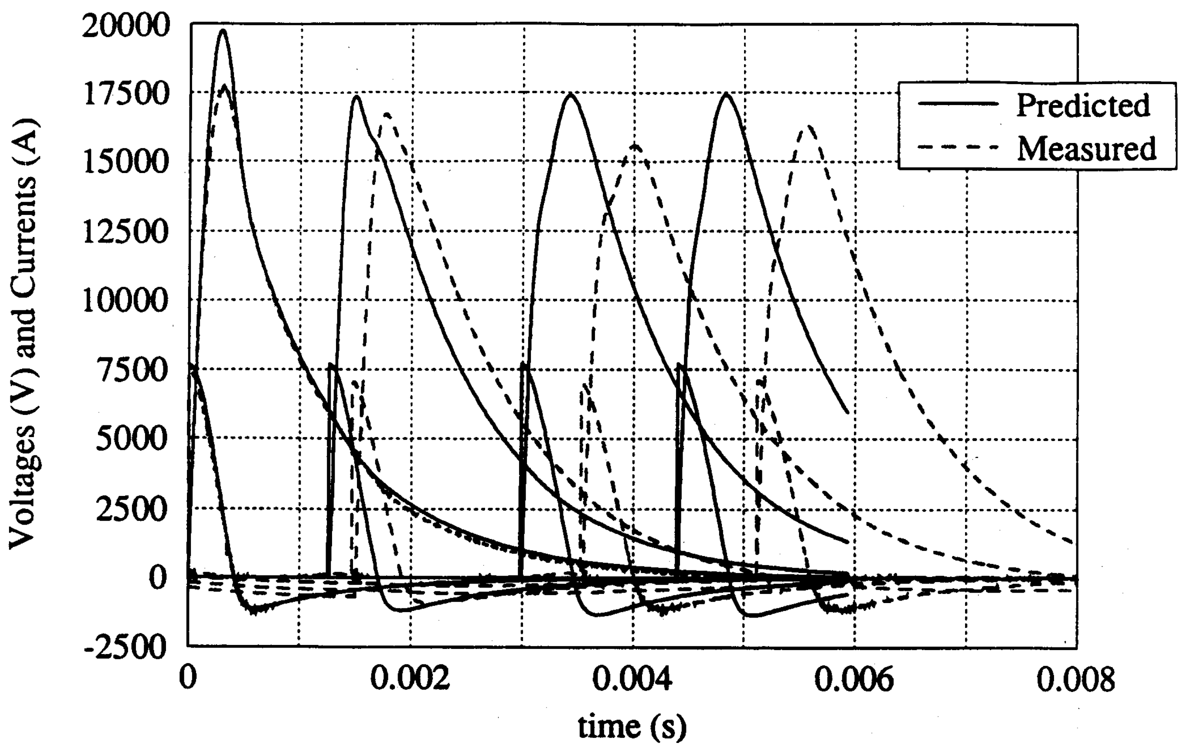

Fig. 1. Predicted and measured coil voltage and current waveforms. Four-stage launch.

TABLE 2

TIME TAKEN TO OPTIMISE COIL ARRAYS FOR GUNS OF DIFFERENT STAGE NUMBERS

Number of Stages	Number of Variables	Computing Time (h : m : s)
1	3	7 : 07 : 23
2	7	32 : 48 : 49
3	11	89 : 45 : 31
4	15	224 : 33 : 48

TABLE 3

4-STAGE STATOR DESIGN BY FORMAL OPTIMISATION

Scheme	Number of variables in each optimisation	Exit Velocity (ms-1	Kinetic Energy (kJ)	Computing Time (h : m : s)
Stage-by-stage	3/4/4/4	301	22.64	51 : 14 : 37
Two overlap	7/8/8	305	23.26	80 : 25 : 09
Three overlap	11/12	310	24.03	130 : 28 : 58
Full optimisation	15	311	24.18	224 : 33 : 48

The results given in Table 2 indicate that full optimisation of guns of more than 5 or 6 stages is practically impossible. Such considerations have lead others [8], [9] to adopt a stage-by-stage optimisation procedure in which the design of each stage is considered in isolation from those that follow it, and with the assumption that the design of all preceding stages has already been determined. In essence the design of an M-stage gun becomes M separate single-stage optimisations. The consequences of adopting this approach are shown by the first row in Table 3 which shows that the four single-stage optimisations reduce the computing time from 222 hrs 34 min to 51 hrs 14 min, but that the resulting design gives a projectile K.E. of 22.64 kJ, instead of 24.18 kJ. Both designs are based on the use of the same 4 x 25 kJ power supply, so the 1.54 kJ reduction in K.E. corresponds to a 1.54% reduction in launch efficiency.
With even more stages the reduction in efficiency arising from the use of stage-by-stage optimisation might be expected to be more severe.

The reason for the degredation in performance of the stage-by-stage approach is thought to be because it ignores inter-stage coupling. The field at a point along the axis of a filamentary coil, distance z from the centre of the coil varies as

$$B(z) = B_0\left(\frac{R^2}{R^2+z^2}\right)^{\frac{3}{2}}$$

where B_0 is the field at the centre of the coil and R is the coil radius. The flux attenuation coefficient, $B(z)/B_0$, is therefore 35.4% at z = R, 8.9% at z = 2R, 3.1% at z = 3R, and 1.4% at z = 4R. These figures show that the influence of a coil will be small at an axial distance equal to three or four times its own radius. This observation leads to the suggestion of an alternative procedure for optimisation, the basis of which is as follows: Stages 1 to N of an M-stage gun (M>N) are designed using the optimisation algorithm to obtain maximum velocity at the exit from the N-th stage. This procedure fixes the design of stage 1. The algorithm is then used to design stages 2 to N+1, which fixes the design of stage 2, and so forth. Such a scheme which ignores the coupling between stages which are N coils apart, may be described as an 'N-overlap' optimisation. It produces a final design in M-N+1 N-stage optimisations. A suitable choice of N may be judged from the mean coil radius and the coil separations, using the amplitude attenuation coefficients given above.

To illustrate this approach, Table 3 lists the performance achieved by the same 4-stage gun designed using two-overlap and three-overlap schemes. Clearly the two-overlap design gives some improvement (compared to the stage-by-stage design) but the three-overlap is closely equivalent to the fully-optimised design, whilst taking 42% less time. The reasons for this may be understood with respect to the flux attenuation coefficients, discussed above. The two-overlap method ignores coupling between coils which are not adjacent to each other. The minimum distance between two such coils in the final design is approximately equivalent to 1.3 radii, giving an attenuation factor of 22%. This shows that there will be substantial inter-coil coupling that is neglected. The three-overlap method includes coupling between coils which are separated by up to one other coil.

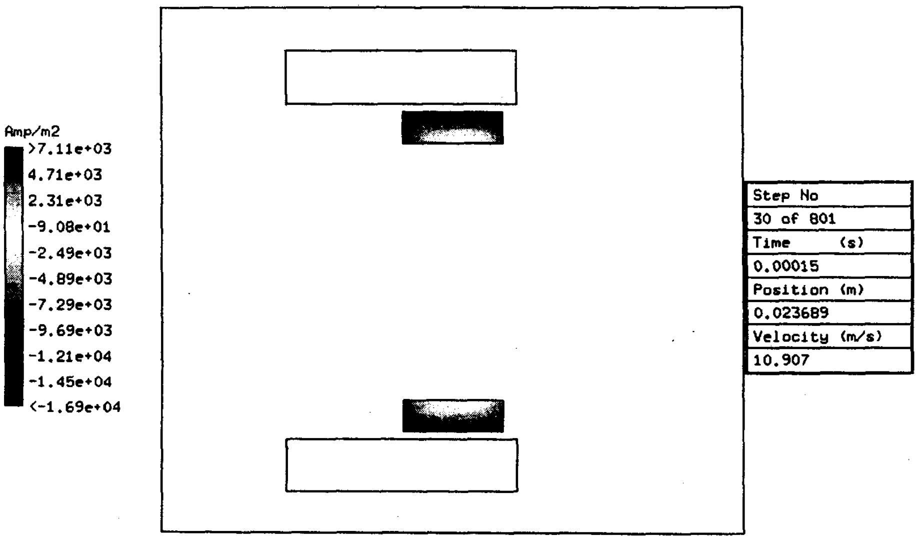

Fig. 2(a). Armature current distribution 150 μs into launch. All currents positive.

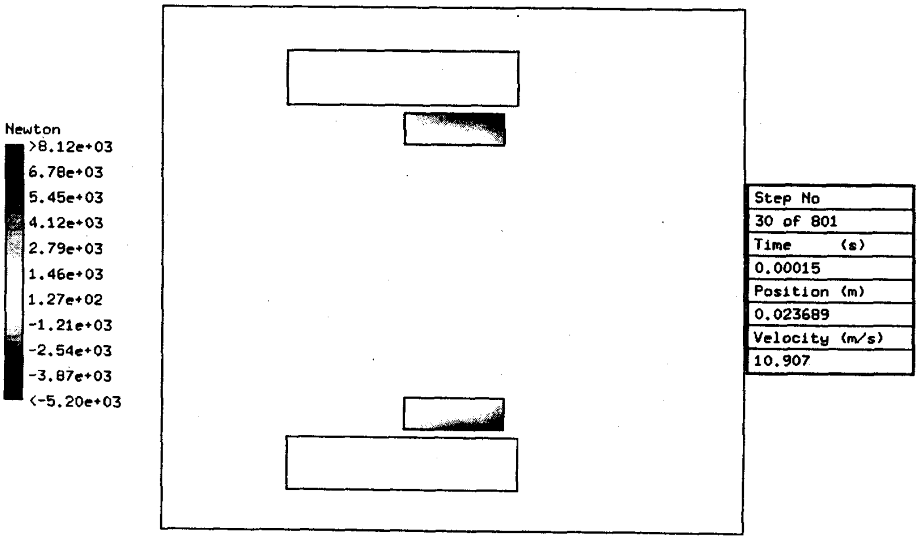

Fig. 2(b). Armature force distribution 150 μs into launch. All forces positive.

The first coupling term that is neglected is therefore between coils that are separated by two other coils. For the four-stage gun this corresponds to approximately 2.5 radii, giving an attenuation factor of 5%. Clearly the three-overlap method gives a far better approximation to a full optimisation, in which all inter-coil coupling is accounted for.

IV. Armature Design

The use of a coupled-circuit analysis to model a monolithic armature requires that armature to be represented as an ensemble of filamentary loops. This form of representation enables important current diffusion phenomena to be taken into account. The filamentary currents are each determined as a function of time during the simulation, and may be used to determine the current distribution over the cross-section of the armature.

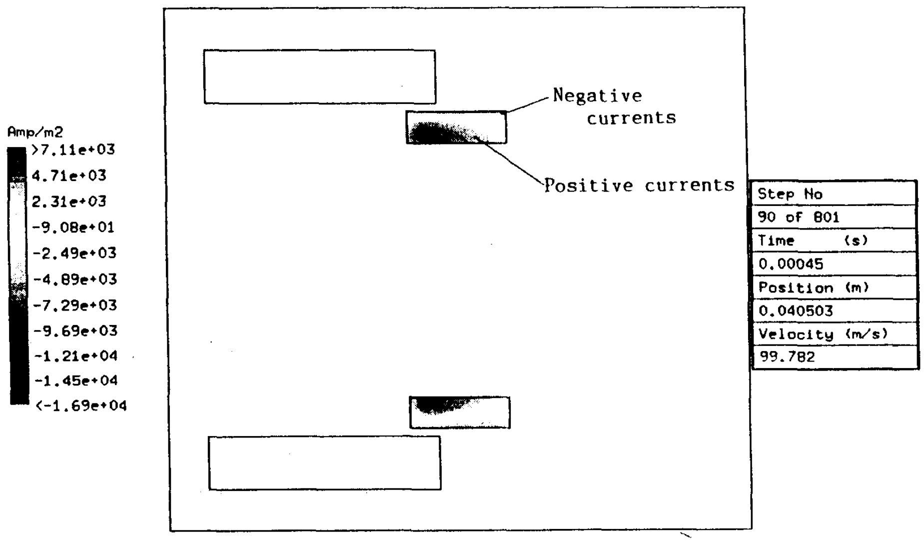

Fig. 3(a). Armature current distribution 450 μs into launch.

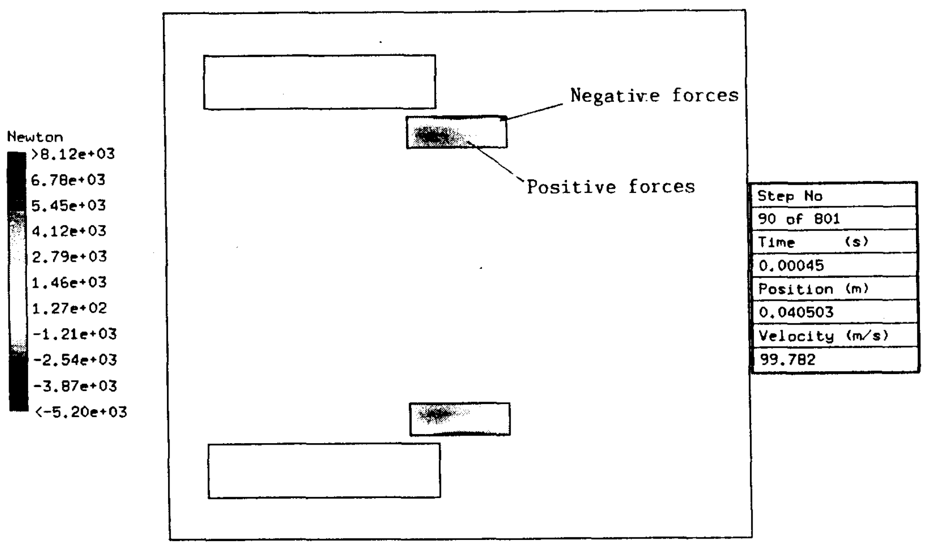

Fig. 3(b). Armature force distribution 450 μs into launch.

Fig. 2(a) shows the armature current distribution 150 μs into a single-stage launch, with the magnitude of the current density being indicated by the intensity of the shading. As expected, there is a concentration of current at the trailing edge of the armature. Fig. 2(b) shows the force distribution across the armature at the same instant in time, indicating that the greatest force is exerted at the leading edge of the armature. The reason for this is quite straightforward. Although the current density at the trailing edge is greater in magnitude, its position is more central relative to the stator coil. It therefore experiences both forwards-acting and backwards-acting forces of closely equal magnitude. These forces tend to balance out. The leading edge of the armature has less current but a greater positional asymmetry with respect to the stator coil, so that the forwards acting forces it experiences far exceed those that act backwards.

Figs. 3(a) and 3(b) show the situation that obtains 300 μs later (i.e. 450 μs into the launch). In Fig. 3(a) the current in the armature is shown to be relatively evenly distributed in the axial sense, but has reversed direction in the outermost skin. This is a consequence of Lenz's Law, as the armature begins to move out of the substantial field that is alreading linking it. Fig. 3(b) shows that the axial force in the outer skin has also reversed but that the bulk of the force is still forwards acting.

The force distributions of Figs. 2(b) and 3(b) suggest a method by which the shape of the armature cross-section might be modified using utility weightings attached to each filament of the armature. Assume that the stator design has been carried out using the procedure described in the previous section. This will have involved the use of an armature of fixed dimensions - and therefore fixed mass which we may assume has been set by the gun specification. The dimensions of this armature may now be increased by adding, say 20%, to its length and reducing its inside diameter by 20%. The simulation program is then run and the average force exerted on each filament calculated. These average forces show how 'useful' each filament is during the launch, and the 10% (say) least useful filaments may be removed. This has the same effect as machining material from the (oversized) armature. This procedure is then repeated, taking away a limited number of filaments at each pass, until the mass of the armature returns to its original value.

The above procedure has been tested by the authors using a simulated single-stage launcher. The profile of the projectile so-produced is given in Fig. 4. The simulation program indicates that this shape will give the projectile an extra 7.1% of K.E., compared to its rectangular-section parent.

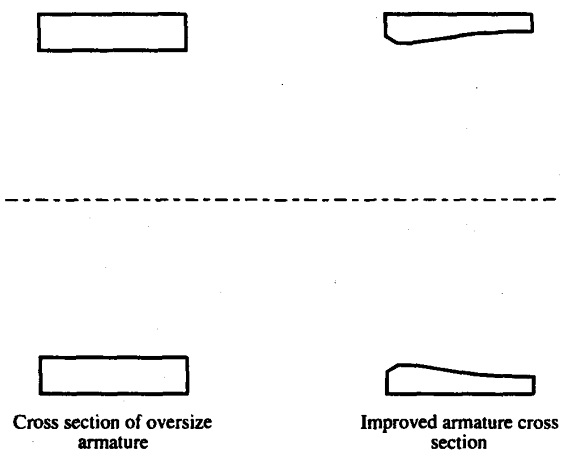

Fig. 4. Changed shape of armature.

V. Conclusions

The authors have proposed a systematic design procedure for multi-stage pulsed coil-guns. The procedure has two distinct phases. The first phase is the design of the coil array which is accomplished using a novel 'overlapped optimisation' technique. The second phase is the design of the rotor which is firstly over-sized, then reduced by the removal of least effective material, resulting in a non-rectangular cross-section.

References

[1] Williamson, S. and Leonard P.J.: 'Analysis of air-cored tubular induction motors', *IEE Proceedings*, Pt.B, 133, (4), pp.285-289, July 1986,

[2] Elliot, D.G.: 'Mesh-matrix method for electromagnetic launchers' *IEEE Trans. on Magn.*, Vol.25, (1), pp.164-169, January 1989.

[3] Widner, M.M.: 'Warp-10. A numerical simulation model for the cylindrical reconnection launcher', *IEEE Trans. on Magn.*, Vol.27, (1), pp.634-638, January 1991.

[4] Pichon, L. and Razek, A.: 'A hybrid f.e.m.-n.e.m. technique for force analysis in tubular induction devices', *2nd European E.M.L. Symposium*, St. Louis, France, pp.IX 2.1-2.9, 1989.

[5] Chang, J.H., Becker, E.B. and Driga, M.B.: 'Coaxial electromagnetic launcher calculations using FE-BR method and hybrid potentials', *IEEE Trans. on Magn.*, Vol.29, (1), pp.655-660, January 1993.

[6] Leonard, P.J., Lai, H.C., Hainsworth, G., Rodger, D. and Eastham, J.F.: 'Analysis of the performance of tubular pulsed coil induction launchers', *IEEE Trans. on Magn.*, Vol.29, (1), pp.686-690, January 1993.

[7] W.H. Press, B.P. Flannery, S.A. Teukolsky and W.T. Vetterling, '*Numerical Recipes in C - The Art of Scientific Computing*', Cambridge University Press, 2nd edition, 1992.

[8] Bresie, D.A., Andrews, J.A. and Ingram, S.W.: 'Parametric approach to linear induction accelerator design', *IEEE Trans. on Magn.*, Vol.27, (1), pp.390-393, January 1991.

[9] Ingram, S.W., Andrews, J.A. and Bresie, D.A.: 'An actively switched pulsed induction accelerator', *IEEE Trans. on Magn.*, Vol.27, (1), pp.591-595, January 1991.