

## Myth or fact? You can increase the force of your solenoid by removing turns. (Part 3 of 3)

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### Conclusion

The number of turns on the coil has only a secondary bearing on the force of a solenoid, which comes about because of the effect on the average turn radius, which determines the winding factor. While adding (or removing) a turn will increase (or decrease) resistance, thereby decreasing (or increasing) the current, this effect on the force is counterbalanced by the fact that adding (or removing) a turn will also increase (or decrease) the magnetomotive force, as shown most simply in (1). Removing turns cannot affect the force unless it results in a reduction in the average turn radius.

There is a common misconception that removing turns increases force by decreasing the overall resistance, thereby increasing current (References 8 and 9). One reason for this misconception is that force CAN be increased by removing a number of turns, although that comes at a disproportionate cost in steady state power, and as a consequence of the effect on winding factor, not as a direct consequence of reduced resistance. This is an inefficient way to increase force, as shown in Figures 9 and 10. In contrast, decreasing the wire gauge or coil length will increase both the force and the efficiency simultaneously, as shown in Figures 11 through 14.

Another factor that may contribute to this misconception is the fact that stronger solenoids taken off-the-shelf generally have fewer turns than weaker solenoids. The primary reason for that, however, is that they also have a thicker wire gauge, which leaves less room in a given space for turns on the coil. A wire with a larger cross-section has a lower resistance per unit length,  $\gamma$ . As shown in (22) and (25), this appears in the denominator of the force equation and thus leads to an increase in force.

The mechanism, of course, is that the larger wire cross-section decreases resistance, which leads to a higher current for a given voltage. Unlike decreasing the number of turns, however, decreasing  $\gamma$  does not produce an inverse effect in the magnetomotive force. As a result, an off-the-shelf solenoid with fewer turns is likely to have more force than one with more turns.

### References

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### Appendix: Using Equation (8) instead of Equation (12)

Note that the inductance,  $L$ , shows up in the numerator of (12), but in the denominator of (8). If we were to repeat the development of (13) through (22) we would therefore find the force growing exponentially with  $x$ , rather than shrinking exponentially with  $x$ , which is precisely the opposite of what we find with real solenoids. This is a case where using idealized components with zero resistive losses leads to a completely incorrect result (perhaps not surprisingly, a similar conundrum can also be posed using ideal capacitors, but that is another story). It is possible to pursue a more realistic derivation from the AC point of view similar to (4), except including the wire resistance:

$$|I| = \frac{|V|}{|Z|} = \frac{|V|}{\sqrt{R^2 - (\omega L)^2}} \quad (\text{A.1})$$

Substituting this into (2), and dropping the magnitude signs yields:

$$\begin{aligned} W &= \frac{1}{2} LI^2 \\ &= \frac{1}{2} \frac{V^2 L}{(R^2 - \omega^2 L^2)} \end{aligned} \quad (\text{A.2})$$

In this expression  $L$  appears in both the numerator and the denominator. When  $\omega L$  is small compared to  $R$  ( $x$  large, armature pulled out of the coil), then (A.2) is similar to (12), resulting in a force-stroke curve that falls with  $x$ . When  $\omega L$  is large compared to  $R$  ( $x$  small, armature in), this equation behaves more like (8), with a factor of  $L$  in the denominator producing a force-stroke curve that rises with  $x$ . This behavior results in the possibility of a force-stroke curve with a local maximum somewhere mid-stroke. This is, in fact an often seen phenomenon in solenoids driven by AC, as pictured in **Figure A.1**:

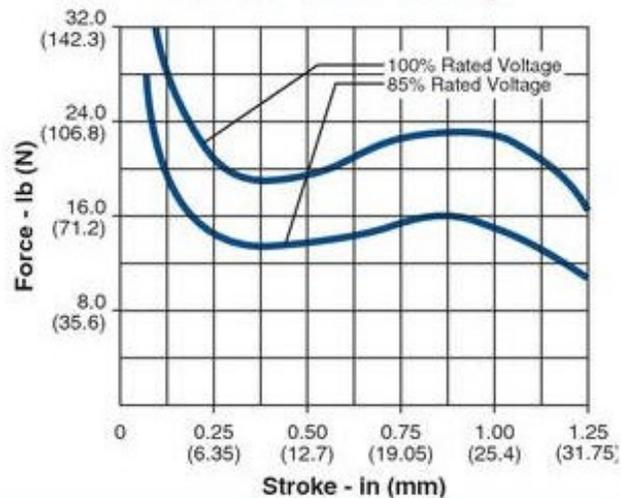


Figure A.1: Force stroke curve for an AC solenoid

### About the author

**Paul H. Schimpf** holds the B.S., M.S., and Ph.D. degrees in Electrical Engineering from the University of Washington, with respective degree specialties in digital electronics, embedded signal processing, and modeling electromagnetic fields in complex domains such as the human body.

He previously worked in the electronics industry for 13 years at Honeywell Marine Systems in Mukilteo Washington (which later became a division of Alliant Techsystems, Hughes Aerospace, and Raytheon), where he attained the level of Senior Principal Development Engineer, prior to entering a career in academics. He was previously a tenured Associate Professor of Electrical Engineering and Computer Science at Washington State University, and is presently Professor and Chair of Computer Science at Eastern Washington University.

One of his hobbies is the restoration and repair of arcade games, of which he presently owns three: a Chicago Coin Twin Rifle (electro-mechanical), a Stern Meteor (early solid state), and a Williams Fish Tales (late solid state). Paul recently designed a printed circuit board to interface an Arduino Mega to 85 different Bally/Stern pinball machines so that his embedded systems students can program pinball game logic using a modern processor. The board includes the capability to play sound effects from WAV files stored on an SD card.