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Usability and Performance Analysis of 3D-Ink-Jet-Printed Load Cells with Resistive and Capacitive Strain Gauges

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Introduction

Strain gauges can be used in a variety of different measurements e.g., to measure forces in manufacturing systems, to continuously monitor displacement of building structures. Furthermore, are they used in simple bathroom scales, kitchen scales and precision instruments with accuracies up to thousands of a gram. We utilize a 3D-Ink-Jet-Printer to manufacture flexible plastic devices with integrated strain gauges consisting of traces for resistive measurements or electrode arrays for capacitive measurements made of sintered silver ink. This additive manufacturing process provides a big advantage in scalability and flexibility over conventional methods and can avoid the necessity of bonding the strain gauges to a substrate adhesively. Printing measuring devices with dimensions of several millimeters up to several centimeters, an adaption to fulfill different geometric constraints e.g., due to housing or mounting, and fine tuning by thinning or thickening materials in particular areas is possible without great effort. Even more or less complex formations of multiple strain gauges combined in one device are feasible. We print different designs and examine them with regard to their sensitivity, hysteresis, non-reversible effects of stress and temperature stability.

Resistive strain gauge

To analyze the feasibility of an inkjet printed force measuring device we designed and printed (figure 1) a rectangular bending beam with two integrated meander-shaped resistive elements. Each of the two elements is placed within a small distance beneath one of the surfaces (top or bottom) to maximize the lengthening or shortening in case a force is applied. The submersion depth is large enough to provide protection to the sintered silver traces against mechanical damage, water ingress or other environmental influences. The beam was mounted on an aluminium plate with the help of a 3D-printed fixture. A plastic weighing pan was added to the tip of the beam and four copper leads were soldered to its connection pads as shown in figure 2.

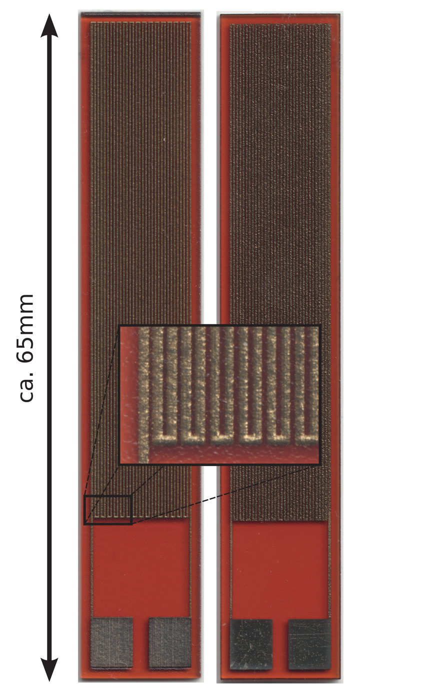

Fig. 1: Top and bottom view of bending beam with integrated resistive strain gauges

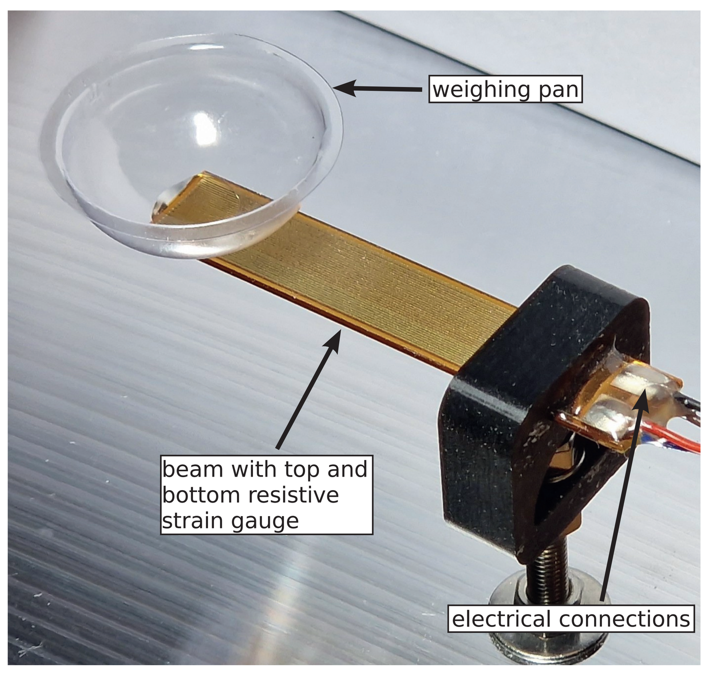

Fig. 2: Mounted and connected bending beam with attached weighing pan

To distinguish the effect of stretch and compression under load the first resistance measurement series for the top and bottom strain gauges were carried out seperately. For each series four different weights (2g, 5g, 10g and 20g) were placed in the weighing pan for a duration of approximately 5 minutes. In order to obtain a rough estimate of the influence of temperature changes on the device each series contains an additional 5 minute period where a hand was held about 10cm above the device. Before and after these periods equilization times of approximately 30 minutes where added. Resistances were measured with a standard 6½ digit multimeter (Agilent 34401A) using 2-wire measurement at a current (internal current source) of about 1mA.
The resistance profile for the top sensor element can be seen in Figure 3 and the profile for the bottom element in Figure 4. A big temperature dependency can be recognized in the first positive peak in both figures caused by infrared radiation from the hand about 10cm above the beam. Also the drift due to the slowly changing ambient temperature is clearly visible although temperatures were kept in a small window of about ∓1°C over time.

The absolute and relative change between the green (baseline) and the red (under load) markers is denoted above the respective peaks. It is noticable that the increase of relative resistance caused by elongation of the top element is considerably higher than the relative resistance decrease caused by the compression of the bottom element. Furthermore the change due to temperature effects in relation to the effect of the loads especially the smaller ones is significantly higher.

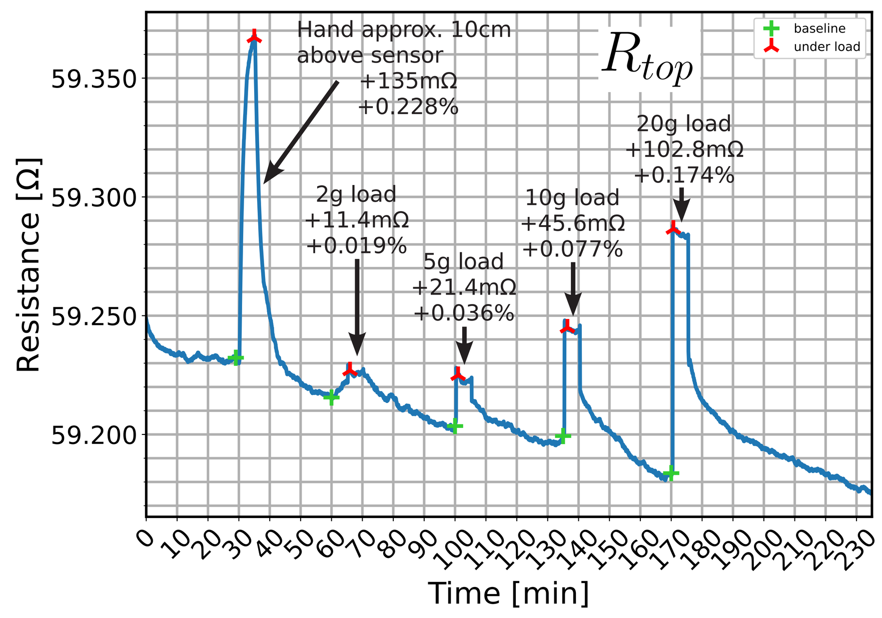

Fig. 3: Result of resistance measurement of top strain gauge

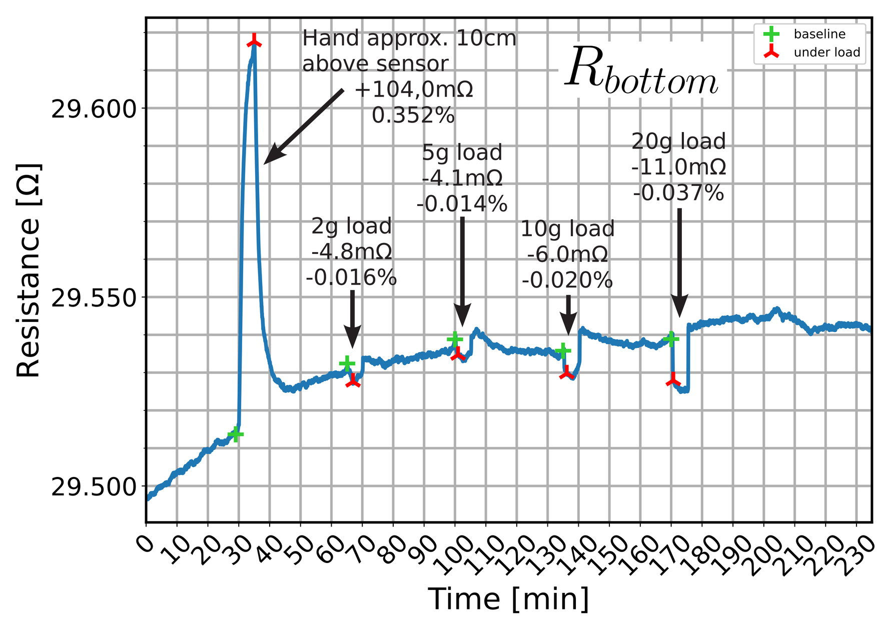

Fig. 4: Result of resistance measurement of bottom strain gauge

Even for conventional manufactured strain gauges temperature changes during measurements are a major problem therfore they are usually used in some kind of bridge configuration the Wheatstone bridge maybe being the most prominent of them.
Most of the advanced bridge configurations in conventional load cells rely on the fact that each resistive track can be produced within small tolerances or adjusted to them by e.g. laser trimming. Thus all strain gauges behave more ore less the same way and by measuring only voltage differences the deviations caused by temperature effects are canceled out.

The 3D-printed integrated strain gauges suffer from much larger differences in resistance as it can be seen for example in figure 3 (about 60Ω) and figure 4 (about 30Ω) which are mainly caused by differences in sintering temperatures during the printing process. Therfore it is more feasible in this case to connect both elements in series, connect a current source to them and calculate the quotient of both voltage drops. The result of a measurement using a 1mA current source and the ability of the Multimeter (Agilent 34401A) to measure the ratio between two voltages can be seen in figure 5 and 6.

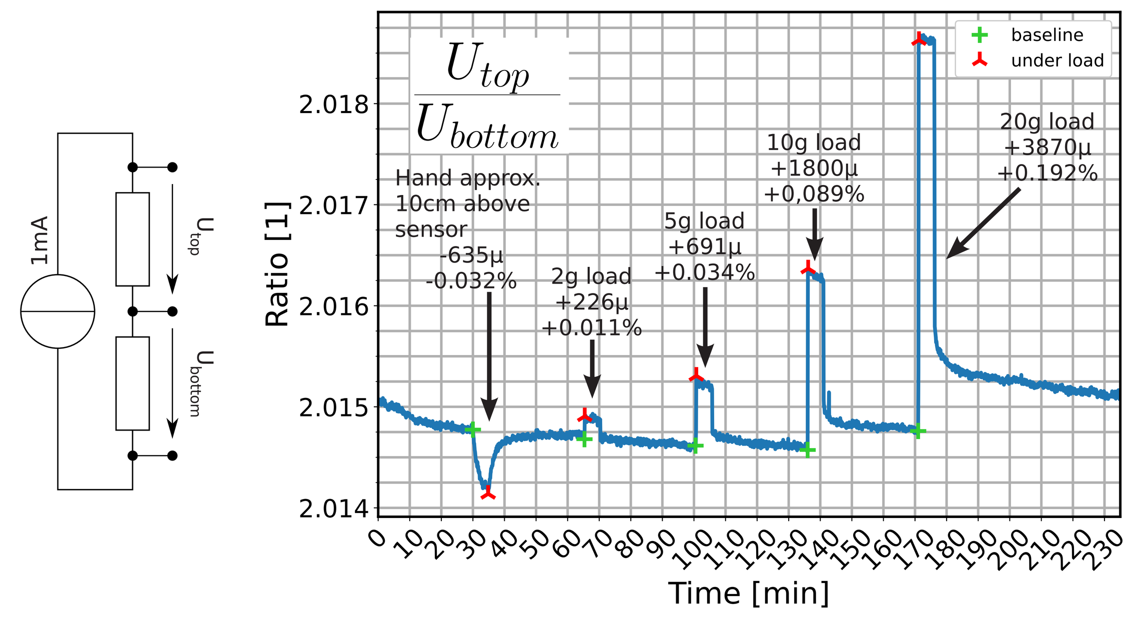

Fig. 5: Result of top/bottom strain gauge ratio measurement

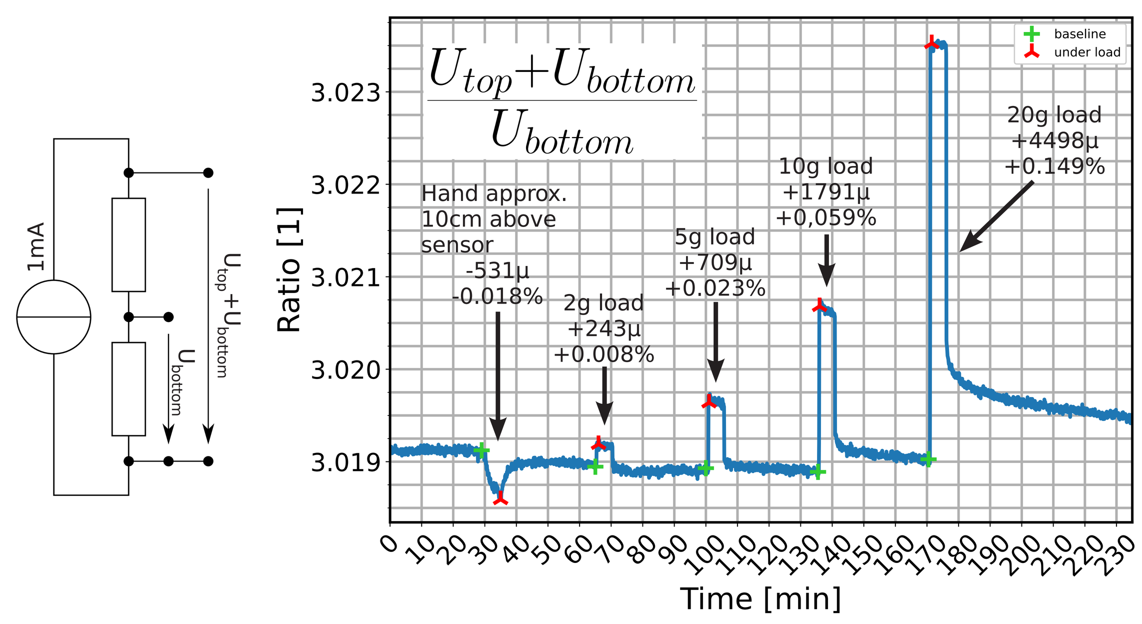

Fig. 6: Result of (top+bottom)/bottom strain gauge ratio measurement

As is clearly visible in both figures the effect of temperature changes is considerably reduced in case of the long term drift it is more or less completely suppressed. The quotient used in figure 6 seems to provide a slightly better performance in that regard.
Now that the drift has been removed a "tailing" effect is visible especially with the larger weigths. It is unclear if it vanishes with enough time or if it is a non reversible overloading effect.

Capacitive strain gauge

A different approach to measure forces is a pendulum that is used as an electrode with its counterpart being a case or frame that also forms the corresponding electrode. The movement of the pendulum leads to a change of capacitance between both electrodes. The resulting capacitor is integrated into a series resonant circuit together with a 50Ω resistor. The circuit is connected to one end of a 50Ω transmission line. If the circuit is excited with a signal that hits its resonance frequency, from the other end of the line, the incoming power is absorbed to a large degree and no or only a very small reflection can be measured at the signal source.

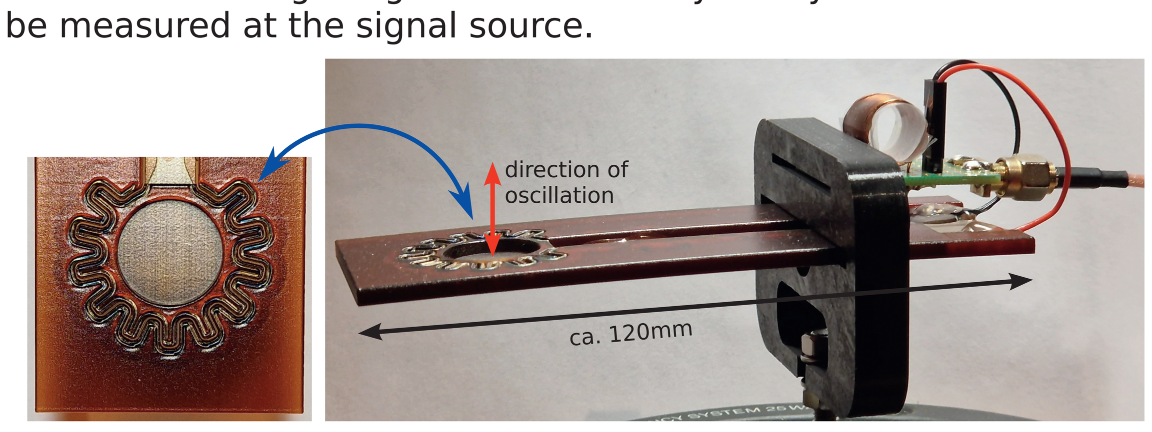

Fig. 8: 3D-Printed pendulum with case/frame, circuit board with coil, 50Ω resistor, SMA connector and printed mounting adapter (right picture). Top view of pendulum electrode area with inner and outer electrode (left picture).

If a spectrum analyzer in combination with a directional coupler is used to measure the reflected signal, while the transmission line is driven over a larger frequency range by a synchronized tracking generator, a return loss profile can be obtained. The resonance frequency is indicated by a dip in the profile, where the reflected power is minimal.
We 3D-printed such a pendulum (figure 8) and analyzed it using the described method. The return loss profile between 20MHz and 27MHz can be seen in figure 9.
When the position of the pendulum and thus the capcacitance changes over time the resonance frequency is modulated with that movement and the point of minimal reflection (dip) is shifted respectively.

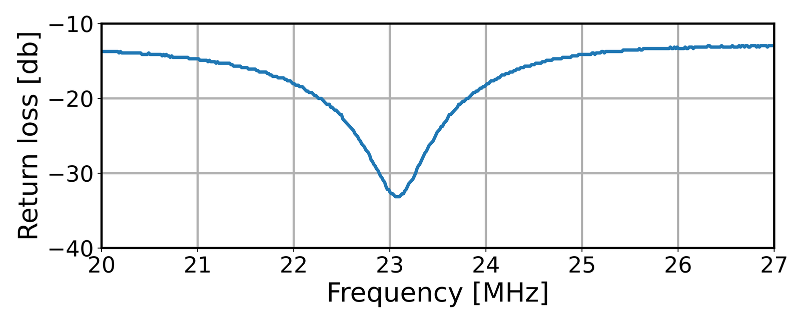

Fig. 9: Profile of reflected power

It is difficult to utilize this feature to derive the resonance frequency because the circuit itself doesn't emit any signals actively. It has to be excited externally to determine the current point of least reflection and that point has to be tracked over time. Another technically less complex option to do so ist to use a single frequency on the linear part of one of the slopes, close to the minimum to achieve an amplitude modulation of the reflected signal as shown in figure 10. A simplified schematic diagram of the used setup can be seen in figure 11. It includes a mechanical excitation mechanism to force the pendulum to oscillate. If a mass is added to that of the pendulum the amplitude of this oscillation is reduced by a certain amount.

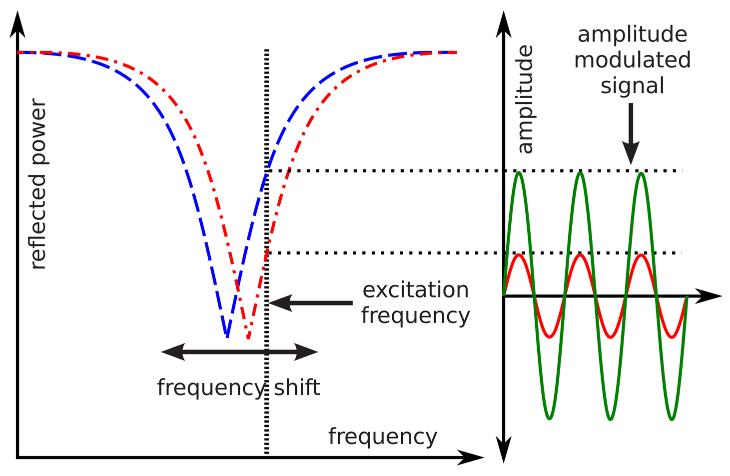

Fig. 10: Frequency shift of resonant circuit due to change of capacitance and resulting amplitude modulation of reflected signal

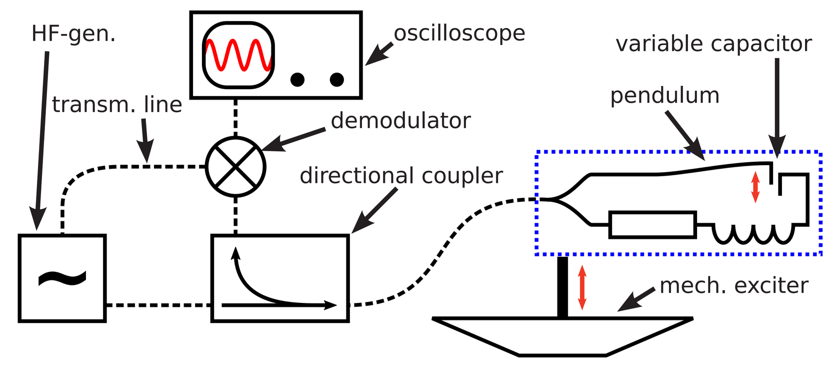

Fig. 11: Simplified diagram of the measurement setup

Figure 11 shows the reflected, demodulated signal for different pendulum loads. As excpected the amplituded decreases with increasing load. In figure 12 the RMS-value for 7 load conditions can be seen. For loads above 1g the systems seems to be saturated. The non symmetrical shape is probably caused by the gravitational load.

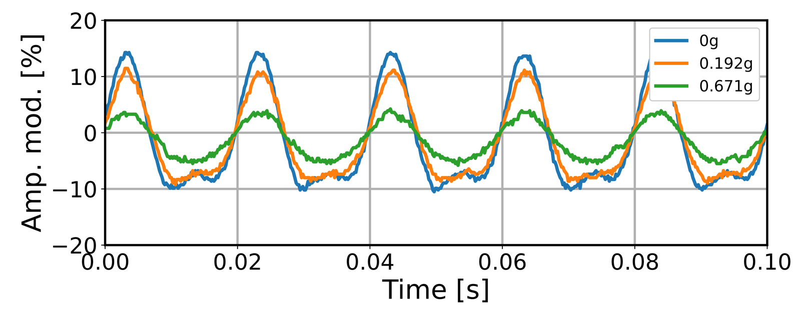

Fig. 11: Reflected signal at no load (RMS value 8.4%), 0.192g (RMS: 6.8%) and 0.385g (RMS: 4.7%)

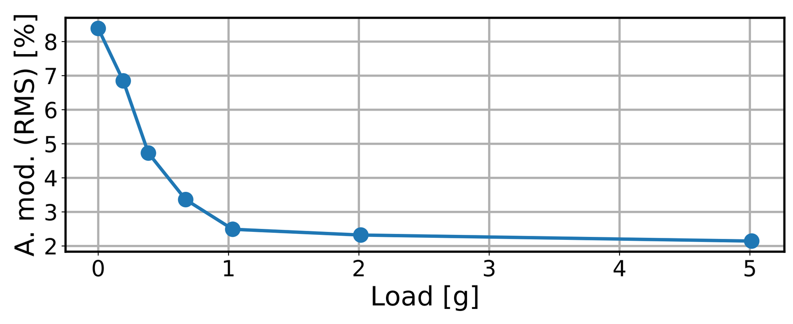

Fig. 12: RMS value of reflected signal at different load conditions

Conclusion / Outlook

It was demonstrated that it is possible to 3D-print working mass/force measuring devices. Both presented methods can be used practically and have their respective areas of application. It is conceivable that the resistive approach can be easily configured for a broad range of loads from 1g up to several 100g. The capacitve approach seems to be more feasible for smaller loads and it is imaginable that it could be optimized for even smaller loads than used above. Temperature effects, linearity and overloading effects need to be analyzed further in order to make a more general statement about the overall performance.

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