Solid-State Joint Actuator for a Vibro Tactile Line Display

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Abstract:
A new actuator concept for a vibro tactile line display based on solid-state joints is introduced. By using piezo stacks in conjunction with the solid-state joints, large deformations with high forces can be achieved. For this purpose, a special cold-rolled spring strip steel is used for the Solid-State Joint Transmitter (SSJT). Due to the layer-by-layer arrangement of the Solid-State Joint Actuators (SSJA), a finger contact area of 9.8mmx5.9mm is achieved with five SSJA. The development of the SSJA was carried out with FEM simulations in order to identify and if possible eliminate areas of critical stress. The finger load on the SSJA is already taken into account during development using a spring-damper model. From the small signal behaviour of the SSJA, a spring-damper model is created and suggested for later control. By means of performance tests, it is shown that large deflections are achieved over a wide frequency range. For this purpose, the SSJA is measured under real operating conditions (when a test person puts his finger on the display).

Keywords: Solid-State Joint, Vibro Tactile Display, Piezo stack,

Introduction

In recent years, the interest in tactile displays has grown increasingly [1], [2]. Especially the area of vibro tactile displays presents the developers with great challenges. This is, for example, frequencies up to 1000Hz with amplitudes ≥100µm under real finger load at a resolution of the display of 1-2.5mm, so that the whole spectrum of mechanoreceptors in the skin can be stimulated well. There are already various approaches at the construction of actuators for vibro tactile displays [2]. Piezoelectric actuators have been shown to be particularly interesting in this area. Piezoelectric bending transducers with their large deformation ranges and adequate forces are no novelty [3, 4, 5] and these are very well suited for shear force excitation. Efforts are now being made to combine the good properties of piezoelectric bending transducers with another actuator in order to obtain both shear force excitation and excitation perpendicular to the finger (normal force excitation) [6]. A normal force actuator concept was pursued, which is based on the reluctance principle. Due to the requirement to use very small components in order to obtain a good resolution of the display, the limits of the reluctance principle with regard to force and deflection were shown. Also piezo stacks have already been installed in tactile displays for normal force excitation. They have high deformation forces but have only small displacements. Especially when using piezo stacks, the transmission of these small displacements is crucial. In [7], the authors have already managed to increase the small deformation paths of the piezo stacks from approx. 15 µm to 50µm at frequencies up to 100Hz by means of a hydraulic transmission. The method of using SSJTs presented here is a promising alternative principle for building a normal force actuator with piezo stacks. The aim is to achieve deflections ≥100µm under finger load over a wide frequency range. For this purpose, the high forces of the piezo stacks are converted to high deflections with a transmission via solid-state joints.

Design preparation

The normal force actuator we present here is designed as a solid-state joint actuator. The mode of operation is as follows (Fig. 1):
As the piezo stacks ① expand, the vertical levers ⑤ tilt outwards. By this tilting, the levers ⑥ pull the actuatorcross ③ upwards.

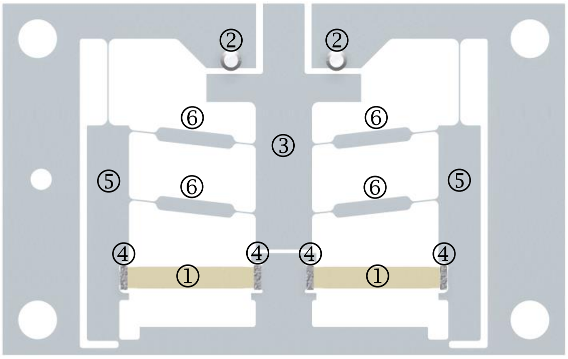

Fig. 1: *The Solid State Joint Actuator (SSJA)*

The SSJA was developed and optimized with the aid of the FEM program ANSYS. The piezo stacks were considered as springs with appropriate stiffness and preload. The static analysis shows that the area of maximum stress occurs in the joints connecting the horizontal levers ⑥ with the actuatorcross ③ (Fig. 1). To ensure that this tension does not exceed 0.4 x tensile strength = 640N/mm² the cylindrical pins ② are inserted, limiting the maximum deflection. This way the maximum stress of the SSJT does not exceed 340N/mm² according to the static analysis. It also shows that the upper limit stop is reached with the cylindrical pins at a force of the piezo stacks of approx. 50N. A ratio of the deflection of piezo stack to the deflection of the actuatorcross of 13.5 results here. In order to describe the dynamic behaviour, a harmonic analysis was carried out in which the finger contact via a spring-damper model was taken into account. The spring-damper model was created from impedance measurements made perpendicular to the finger. The model is created in the same way as in [8] with the difference that it is not for the lateral excitation of the finger, but for the normal excitation of the finger. This model is used to ensure that the required deflection of ≥100µm can be achieved over a wide frequency range even under load. Figure 2 depicts a result from the modal analysis of the SSJT model at its first resonance frequency of approx. 410Hz. Figure 3 depicts the calculated deflection of the SSJT over the frequency under load condition with the finger load model. It depicts that the SSJT achieves the required deflection up to a frequency of 600Hz. Above 600Hz it is not achieved even with the maximum force of the piezo stacks. This could result from the more complex contact scenario with the finger and from the fact that the resonance frequency has already been passed. The load model is firmly coupled to the actuator but in reality, however, the actuator cannot transmit tensile force to the finger. The excitation voltage is determined by the relationship $U = \left(\frac{U_{\max}=120\mathrm{V}}{F_{\max}=210\mathrm{N}}\right) F$.

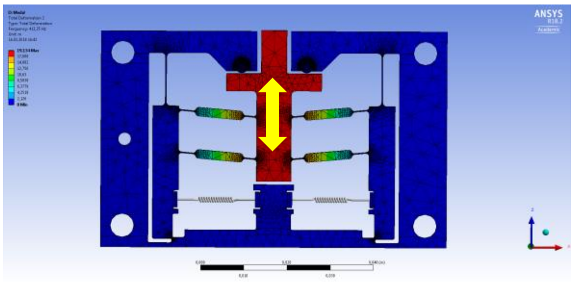

Fig. 2: *First resonant frequency of the SSJT at approx. 410Hz with a yellow arrow representing the direction of movement*

Design

Each actuator uses two piezo stacks ① (P-882.51; PICMA® Piezoaktor) (Fig. 1). The piezo stacks have a maximum displacement of 18µm and a blocking force of 210N. They are particularly suitable due to their small dimensions of 3mm x 2mm x 18mm. The symmetrical arrangement of the piezo stacks ensures a linear deflection of the actuator.

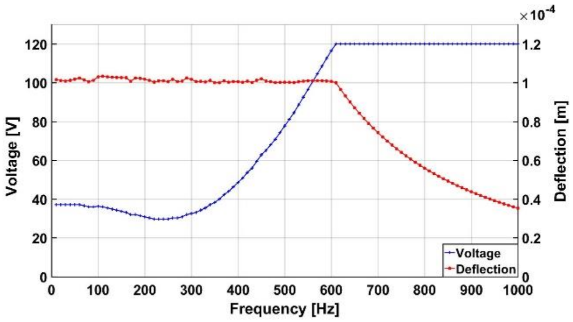

Fig. 3: *Simulated deflection (red) of the SSJT over the frequency under load condition with the finger load model, Excitation voltage (blue)*

For the installation of the piezo stacks, the cylindrical pins ② are not yet installed in the Solid-State Joint Transmitter (SSJT). The actuatorcross ③ is manually steered upwards as far as possible, allowing the insertion of the piezo stacks and the spacer plates ④. The spacer plates were fabricated with high precision, enabling a precise setting of the preload of the piezo stacks, once the actuator is relieved. This way designed spacer plates, a preload path of 15µm on each piezo stack is guaranteed. As a result, the piezo stacks are operated in the pressure range exclusively. Then the piezo stacks are fixed with epoxy. Now the cylindrical pins ② are put in place to limit the maximum deflection during operation in order to protect the material of the SSJT from fatigue fracture. If the deflection becomes larger than desired, the actuatorcross pushes against the cylindrical pins. To ensure that the vibrations generated in the actuator do not cause a breakout of the piezo stacks from their attachments, they are fixed with the epoxy. The SSJT consists of a cold-rolled spring strip steel (X10CrNi18-8) with a tensile strength of 1600N/mm² - 1800N/mm². This high tensile strength is necessary to ensure that the joints can withstand the high stresses caused by the deflections. The dimensions of the SSJT is 80mm x 1mm x 50mm. The SSJTs were produced by wire eroding to ensure the required tolerances of a few µm, especially in the bending zones. Five of these actuators are assembled in layers to form a linear display. The cylindrical pin ⑦ (Fig. 4) ensures that the actuators are aligned in the housing. Between the actuators, layers of Teflon film are applied to ensure a defined distance between the actuators. Due to the selected distance, a gap of approx. 50µm is achieved between the individual distance plates ④ (Fig. 1).

Modeling

In order to get a control model, the behaviour in the small signal range is considered. This behaviour can be described using the electromechanical analogy [9, 10, 11] with a spring-mass damper model (Fig. 5). The piezo stacks are considered with their quasi-static model.

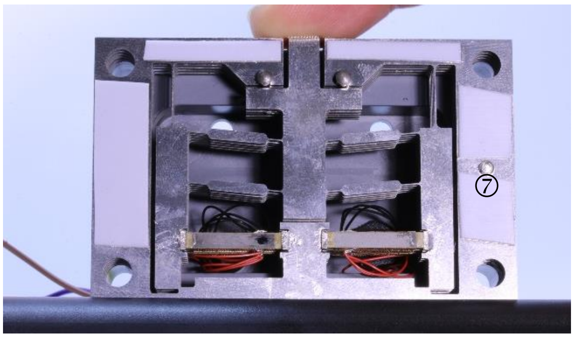

Fig. 4: *The one side opened vibro tactile line display*

It must be taken into account that there are two piezo stacks in each actuator, when selecting the parameters. The capacitance $C_{\mathrm{P,total}}$ and the stiffness $k_{\mathrm{P,total}}$ in the model derive from the parallel connection of the two piezo stacks. The coordinate x describes the deflection of the piezo stacks. The charge Q corresponds to the electrical coordinate and the voltage U corresponds to the excitation of the system. The transmission factor α_1 corresponds to the translation of the electrical signals into mechanical signals. The coordinate y corresponds to the movement of the actuator at the finger contact surface. The factor α_{Solid} derives from the FEM analysis and corresponds to the translation of the SSJT from the static analysis. This value can vary due to the geometric non-linearity in relation to the deflection or frequency, but here it is linearized and assumed to be constant. The SSJT is described with the moving mass m_{Solid} from the CAD model, the k_{Solid} and the attenuation d_{Solid}. The individual parameters are listed in Table 1.

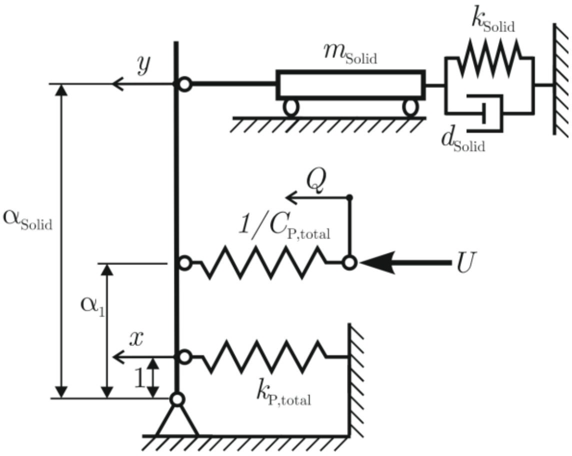

Fig. 5: *Model of a Solid State Joint Actuator (SSJA)*

The amplitudes of the model can be described using the following equations:

$$\frac{\hat{I}}{\hat{U}} = \frac{\mathrm{j}\,\Omega\,\alpha_1{}^2}{\alpha_{\mathrm{Solid}}{}^2\,T - k_{\mathrm{P,total}}} + \mathrm{j}\,\Omega\,C_{\mathrm{P,total}} \tag{1}$$

$$\frac{\hat{y}}{\hat{U}} = \frac{\alpha_1\alpha_{\mathrm{Solid}}}{\alpha_{\mathrm{Solid}}{}^2\,T - k_{\mathrm{P,total}}} \tag{2}$$

With:

$$T = (-\Omega^2 m_{\mathrm{Solid}} + \mathrm{j}\Omega d_{\mathrm{Solid}} + k_{\mathrm{Solid}}) \tag{3}$$

Here j is the imaginary unit, Ω the angular frequency, $\hat{I}$ the current amplitude, $\hat{U}$ the voltage amplitude and $\hat{y}$ the velocity amplitude of the SSJA. Fig. 6 compares the measured admittance of an SSJA with the model. An excitation voltage of $U_{\mathrm{pp}} = 1\mathrm{V}$ with an offset of $U_{\mathrm{DC}} = 1\mathrm{V}$ was used for the measurement.

Table 1: Parameters of the SSJA Model

Capacity of both piezostacks	$C_{\mathrm{P,total}}$	6.8e-7 [F]
Stiffness of both piezostacks	$k_{\mathrm{P,total}}$	2.7e+7 [N/m]
Electromechanical transmission factor	α_1	0.571[N/V]
SSJT factor	α_{Solid}	13.5 [m/m]
Moving mass of the SSJT	m_{Solid}	0.006 [kg]
Stiffness of the SSJT	k_{Solid}	1.7e+5 [N/m]
Attenuation of the SSJT	d_{Solid}	0.4 [Ns/m]

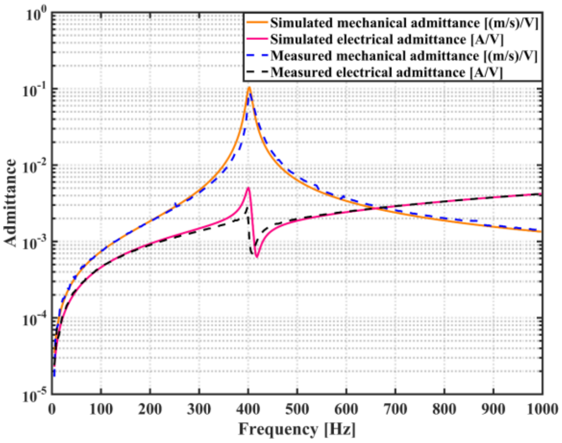

Fig. 6: *Comparison of the measured and modelled admittances*

Performance test

For the performance test, a test person put his finger on the display. The display is positioned on a scale so that the person can apply a static preload of approx. 50g to the actuators. The display is open on one side so that the movement can be detected by a optic fibre vibrometer (OFV-552, Polytec) with the controller (OFV-5000, Polytec) and a decoder VD-09 from below on the actuatorcross. The angle of the laser resulting from this position is taken into account in the data evaluation. The voltage is measured with a differential probe (HAMEG instruments; HZ109). The current is measured with a current probe and a TCP A300 Tektronix amplifier. The excitation is carried out by a function generator (NI PXI-5402, 14Bit 20MHz FGEN) via an amplifier (NF; HSA 4052). The measurement data is recorded with a measurement board (NI PXI-5105, 12-Bit 60MS/s Digitizer). The excitation voltage for an actuator is a sine signal with an offset. The voltage is increased until a deflection of 100µm is reached. Fig. 7 depicts the deflection over frequency and the excitation voltage. The lines represent 10µm steps. The range >100µm was not measured and therefore cannot be evaluated. A deflection of 100µm is achieved up to a frequency of 500Hz under realistic load conditions. However, above 500Hz, a non-linear behaviour was observed as a function of the excitation voltage. Thus, it could be observed that if the deflection at e. g. 10.00V excitation voltage was still at approx. 12µm, only 20mV more result in a deflection of >120µm causing the actuator to hit against the upper deflection limiter. In order to ensure further functionality, the area was not measured any further, because this type of movement represents a high mechanical stress on the solid-state joints. The behaviour was also evident in the loaded state with the finger on the display. This behaviour means that the actuator should not be operated above 500Hz.

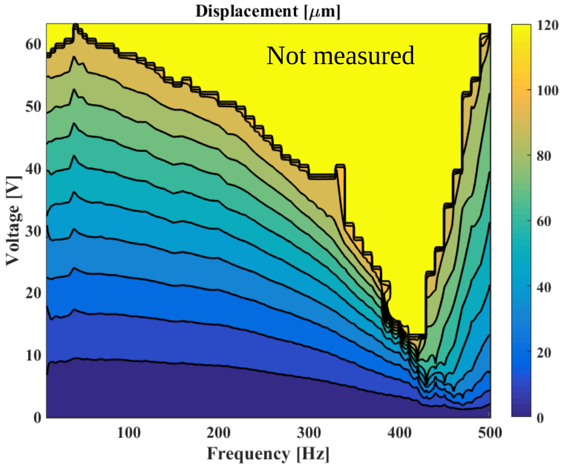

Fig. 7: *Displacement under finger load over frequency and voltage*

Conclusion

It was shown that with a SSJT it is possible to transform the small deflections and large forces of the piezo stacks into sufficient deflection and force for the application in a tactile display. At this time, deflections ≥100µm for a frequency range up to 1000Hz under real finger load are not possible. However, we could achieve these deflections for frequencies up to 500Hz. Regarding the performance achieved using a hydraulic transmission in [7], the displacement was doubled and the highest possible frequency is five times as high with the SSJT under load conditions. The behaviour of the SSJA can be described very well with the help of the presented substitute model. Above 500Hz and for larger excitations non-linear effects occur, which partly originate from the geometric non-linearity of the SSJT. Simplified the actuatorcross looks like a mass excited by inclined springs. Nevertheless, a SSJT for tactile displays offers excellent prerequisites. For more actuators in a tactile display, a further miniaturization of the SSJT is quite conceivable. During the performance tests it was not possible to block the actuators by manual force even for very low frequencies < 5Hz. This is due to the high forces of the piezo stacks of up to 210N, which suggests the thought that only one instead of two piezo stacks is sufficient for proper excitation. We are convinced that the use of solid-state joints in tactile displays is an area that can bring many innovations in the future.

Acknowledgements

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