

DESIGN AND OPTIMIZATION OF NONLINEAR OSCILLATORS FOR DRAG REDUCTION ON AIRFOILS

Muhammad bin Mansoor, Soeren Koeble, Peter Woias and Frank Goldschmidtboeing
Laboratory for Design of Microsystems, IMTEK - University of Freiburg, Germany

ABSTRACT

We demonstrate a novel resonant and nonlinear piezoelectric oscillator design for the manipulation of the turbulent boundary layer on airfoils. A thorough analysis of the system's non-linear dynamics has helped to convert the abrupt, chaotic and irregular response to a desirable smooth hardening response. The high-force actuators realized amplitudes of 500 to 700 μm in the frequency range of 900 to 1200 Hz, while the MEMS counterpart shows a stroke of up to 250 μm in the same frequency range.

INTRODUCTION

Turbulent flow has been a major research topic in aerodynamics since the turn of last century when Ludwig Prandtl first presented his theory on boundary layer flow. An active manipulation of the turbulent boundary layer offers a promising route to influence wall shear stress and hence skin friction seen on airfoils, in order to reduce drag and fuel consumption. Experimental and numerical studies have shown that introduction of a transverse travelling surface wave in the turbulent boundary layer can help to decrease the frictional drag [1, 2]. Other low frequency manipulation mechanisms have also shown to influence drag [3, 4]. On the other hand, Adrian et. al. have proposed that fully developed turbulent flow can be actively manipulated via high stroke actuation ($\geq 1\text{ mm}$) in a frequency range from 1 to 10 kHz [5].

Two different actuator designs, in order to achieve such high frequencies, have been fabricated and tested during the course of this work. The Inverse piezoelectric effect offers an energy-dense actuation mechanism suitable for fast system dynamics. Operation near resonance provides an energy-efficient window and the self-induced nonlinearity in the system creates a broadened operational bandwidth.

The high-force nonlinear resonant oscillator design features a piezo-stack actuator. Such a design offers high stroke at relatively higher frequencies but is limited in its miniaturization potential. For creating a traveling surface wave, an array of stream-wise or span-wise cascaded actuators is desired. For this reason a MEMS counter-part, featuring piezo strips on a clamped brass membrane, is also optimized and fabricated.

THEORETICAL BACKGROUND

A fully clamped metallic membrane necessarily stretches as it vibrates in its transverse motion. This effect can be neglected as long as the amplitude of transverse vibration is kept smaller than the membrane thickness. However, large amplitude vibration of a fixed metallic membrane (stroke exceeding the thickness of the membrane itself) leads to in-plane stresses in the neutral plane. This geometrically induced stretching of the mid-plane creates a nonlinear restoring force, commonly

modeled as an additional nonlinear spring. This nonlinear force enters the equation of motion in a form proportional to the cube of displacement. The dynamic displacement z of mechanical oscillators with nonlinear stiffness under external excitation F_{ex} is usually described by the non-dimensional Duffing equation:

$$\ddot{z} + 2\zeta \dot{z} + z + \gamma z^3 = F_{ex} \cos(\Omega t) \quad (1)$$

In this equation ζ is the damping constant, Ω the normalized excitation frequency and γ the nonlinear spring constant. Such systems are classified based on the type of non-linearity as softening ($\gamma < 0$) or hardening ($\gamma > 0$) as shown in Figure 1.

The principle of linear superposition can no longer be used to calculate the forced frequency response. In addition, for nonlinear systems the steady-state response depends on the chosen initial conditions. The maximum response also does not occur close to the system's natural frequency. Nonlinear restoring forces create the inherent hysteresis seen in the system dynamics (shown with arrows in Figure 1). Phase plane analysis in the vicinity of singular points shows the presence of *saddle node bifurcation* explaining the so-called *jump phenomenon*. Secular perturbation analysis gives a detailed insight into the enriched nonlinear dynamics of the duffing equation [6].

The phenomenon of *secondary resonance* or *nonlinear resonance* is also exclusive to nonlinear systems. Even when the excitation frequency is away from the natural frequency, nonlinear systems can experience resonance. *Superharmonic resonance* occurs when the system resonates to an excitation frequency that is one-third of the systems natural frequency ($\Omega \approx 1/3$). The resonance associated with the case, where the system is forced close to three times the system's natural frequency, is called *subharmonic resonance* ($\Omega \approx 3$).

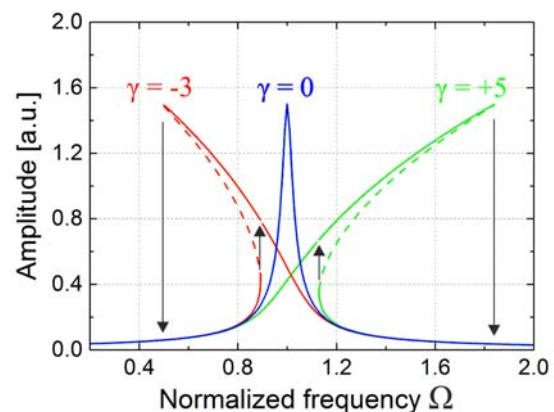


Figure 1: Normalized frequency response curves of a Duffing oscillator. Parameter values used to construct these response curves are $F_{ex} = 0.3$ and $\zeta = 0.1$.

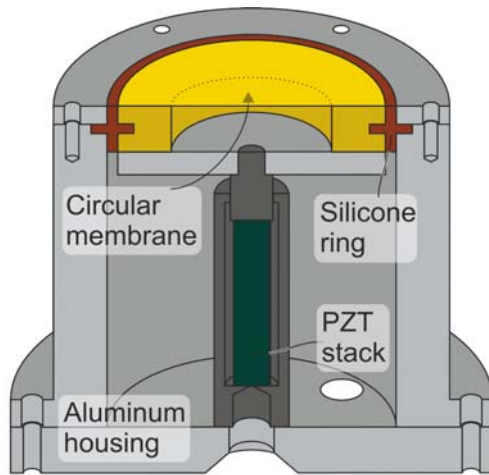


Figure 2: Cross sectional view of the resonant actuation design. Piezo stack actuator excites the brass membrane to vibrate in resonance.

NONLINEAR RESONANT OSCILLATOR

Design

The design concept entails the required challenges from the realms of aerodynamics and continuum mechanics. The actuated surface should be able to align smoothly to the airfoil surface both for experiments in a wind tunnel during Particle Image Velocimetry (PIV) measurements and for a later application. Furthermore, high frequency operation induces extremely high accelerations and thus high restoring forces. Therefore the dynamic mass needs to be as small as possible.

Keeping these challenges in mind, a brass membrane is constructed carefully on top of a piezo stack actuator (P-842.2, PI GmbH Lederhose, Germany), which later on becomes part of the airfoil surface itself. The stack actuator excites the membrane into resonance while the whole assembly operates off-resonance. A cross sectional view of the nonlinear resonator is shown in Figure 2. A detailed analysis on the choice of actuation principle and design can be found in our earlier work [7].

Dynamic characterization

The experimental setup used to characterize the dynamic properties is shown in Figure 3. A sinusoidal excitation signal, generated via a frequency generator is fed to a high voltage amplifier (E-617.00F, PI GmbH Lederhose, Germany). This amplified signal operates the stack actuator and excites the brass membrane to vibrate at its resonance frequency. The stroke of the brass membrane is recorded by a laser vibrometer (CLV 2534, Polytec GmbH Waldbronn, Germany) for a range of excitation frequencies and amplitudes.

Results and discussion

Figure 5 and 6 show the upsweeps curves for two brass membranes with different diameters. The typical Duffing-type hardening is clearly visible in the frequency response. The design of the brass membrane, especially its thickness and diameter, define the frequency range of the oscillator (see Figure 4). Due to this hardening behavior, the actuator can achieve much higher strokes in a broader range of frequencies as compared to a linear

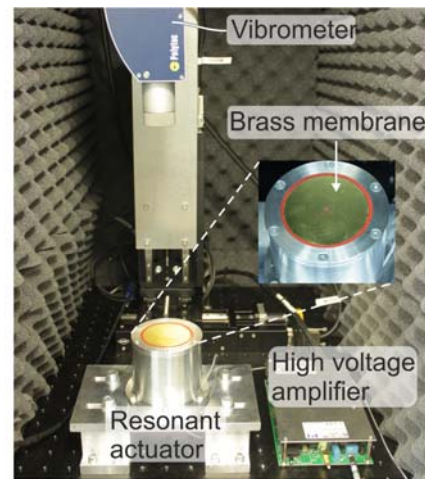


Figure 3: Experimental setup showing the dynamic characterization scheme.

oscillator with comparable mechanical quality factor.

This increased bandwidth provides an ample frequency window to use such an oscillator near its resonance frequency for maximum stroke operation during the planned wind tunnel experiments. However, reproducible disturbing spikes, seen in the original frequency response (black curves in Figure 5 and 6), hinder a controllable manipulation of the turbulent flow.

The excitation-dependent response of the hardening type oscillator, in case of strong excitation, shows a very broad bandwidth. This leads to a higher probability of complex interaction of super harmonics from the second symmetric vibration mode with the degenerate mode itself. First three natural frequencies of a circular plate are $\omega_1 = 10.2158$, $\omega_2 = 39.7711$ and $\omega_3 = 89.1041$ [8]. A unique relationship exists among these symmetric eigen modes:

$$\omega_1 + 2\omega_2 = 89.758 \approx \omega_3 \quad (2)$$

Hadian et. al. have argued that due to this relationship, an *internal* or *autoparametric resonance* is responsible for the nonlinear coupling of involved modes [9].

In order to further analyze the proposed hypothesis, a

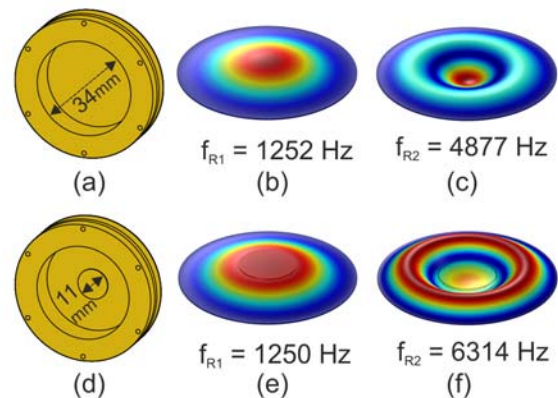


Figure 4: (a, b and c) Brass membrane and its first two symmetric eigen modes; (d, e & f) Brass membrane with an additional center mass and the corresponding symmetric eigen modes.

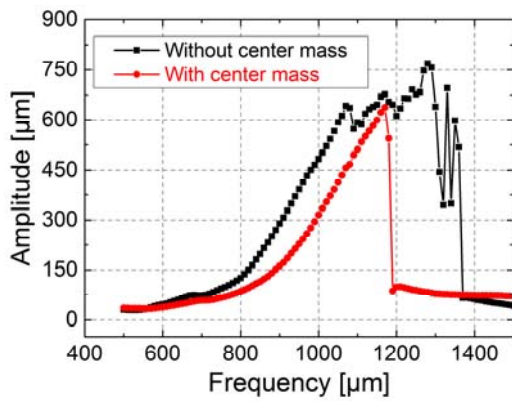


Figure 5: Frequency response curves of a 34mm diameter brass membrane (200µm thickness).

small “center mass” is glued to the original brass membrane that increases the mass of the membrane by the same factor as its stiffness (see Figure 4-d). The diameter of the center mass is chosen to keep the degenerate eigen mode at the same frequency while shifting the second symmetric mode to about 1.4 kHz higher in frequency. Predominantly, the nonlinear coupling of the higher symmetric modes is now avoided leading to the intended smooth hardening response (see Figure 5 and 6).

MINIATURIZED MEMS RESONATOR

Design

The design principle of the MEMS resonator is inspired from the well know bimorph effect. Instead of a circular membrane, a rectangular membrane is used to enhance the ability to cascade such actuators in a row. Miniaturization is desired to use the actuators for experiments in a tri-sonic wind tunnel where a maximum height of only 25 mm is available. The initial design was also presented elsewhere this year [10].

The MEMS resonator consists of two symmetric piezo strips (the active layer) glued to a fully clamped rectangular brass membrane (the passive layer) as seen in Figure 7. By applying an external electrical field, the piezo strips expand (or contract) generating mechanical stress in the bilayer structure. This inhomogeneous stress distribution creates a constant bending moment leading to the deflection of the membrane. The piezo’s are excited at frequencies near the natural frequency of the membrane so that it vibrates in resonance (cross sectional view shown in Figure 8).

The desired operational frequency can be easily adjusted by controlling the thickness of the brass membrane. Different geometrical parameters of the

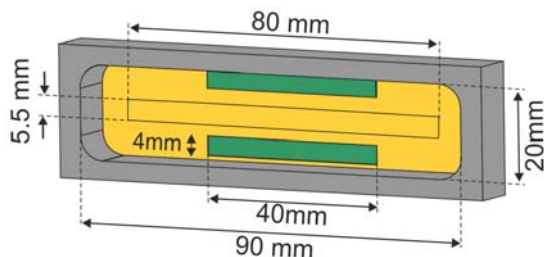


Figure 7: Modified miniaturized MEMS resonator design with center mass.

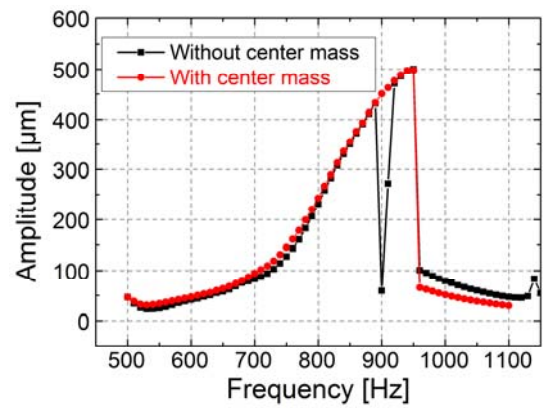


Figure 6: Frequency response curves of a 40mm diameter brass membrane (200µm thickness).

actuator were optimized to obtain highest possible amplitudes. The limiting factor for maximizing the stroke is the mechanical failure of brittle piezo ceramics that brake away for high excitation amplitudes. Piezo ceramics are known to be particularly sensitive to tensile loads. Therefore the optimization criterion for the miniaturized actuators is to have smallest possible bending stresses on the piezo while achieving maximum stroke of the vibrating membranes.

Results and discussion

Figure 9 shows the frequency response curves of the miniaturized design. As the excitation amplitude increases, the bandwidth and maximum displacement also increase. This leads to a wider hysteretic window as visible in the hardening response of Figure 9. A similar spike, as seen in case of the high-force piezo stack actuator, is also observed in the 220 V_{pp} excitation curve.

In order to influence such spikes, a similar approach is applied. A brass strip acting as the center mass is glued in between the two piezo strips to move the consecutive symmetric modes further apart in frequency. Response curves, shown in Figure 10, depict a conversion of the “strictly hardening” response to a “slight-hardening” response. Without any center mass, the peak amplitude frequency (also called the nonlinear resonance frequency) shifts forward with increasing excitation amplitude. On the other hand, with the introduction of the center mass, the nonlinear resonance frequency shifts backwards with the increasing excitation amplitude (a characteristic softening behavior). Nevertheless, the individual curves in Figure 10 still depict a relative hardening jump.

This effect could possibly be explained based on the fabrication method used to construct these actuators. In order to achieve a smooth surface finish, brass membranes

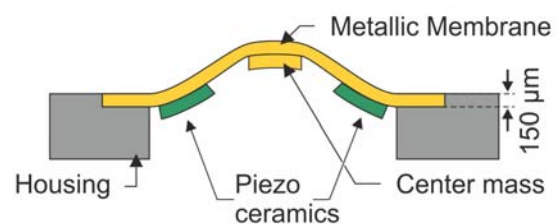


Figure 8: Cross sectional view of the MEMS resonator vibrating in resonance.

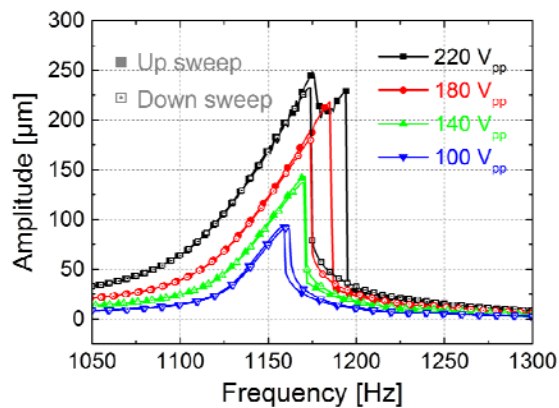


Figure 9: Frequency response curves of the miniaturized design without “center mass”.

were glued with an epoxy adhesive to the aluminum housing. The adhesive layer could also act as an additional spring if the shear stiffness of the adhesive layer is comparable to induced stiffness in the membrane due to high amplitude bending. This additional spring damps the frequency response and changes the overall stiffness of the membrane. Additionally, imperfections in the fabricated actuator could also lead to the evident lower nonlinear resonance frequency. However, sudden spikes in the frequency response can now be avoided.

CONCLUSION AND OUTLOOK

Commercially available high power piezo stack actuators are used to achieve very large displacements ($> 700 \mu\text{m}$) at relatively higher frequencies. Miniaturized approach offers the ability to cascade the actuators but at a cost of reduced stroke. In both scenarios, membranes without center mass show irregular chaotic fluctuations in the frequency response before the corresponding jump down frequencies. Nonlinear coupling of higher order modes, seen evidently for the case of circular membranes, imply that the excited mode is not necessarily the only dominant mode that vibrates. With the introduction of a center mass, these fluctuations disappear while relatively larger bandwidths and higher strokes are still achievable. Both design concepts depict sufficient suitability and durability to be used in wind tunnel experiments. PIV results with and without the actuated surface will further validate the resonant design in future test series.

The increased bandwidth of the actuated surface offers versatility. The miniaturized design would be further optimized based on compliant material properties. Next, the miniaturized design will be extended step-by-step to an integrated array consisting of cascaded actuators creating the desired high frequency travelling surface wave.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support from the Federal Ministry of Economics and Technology under the program LuFo V-1 “Ökoeffizientes Fliegen”. The Project consortium also includes research groups from Airbus, Airbus Group, DLR Göttingen, Universität der Bundeswehr München, Universität des Saarlands and RWTH Aachen.

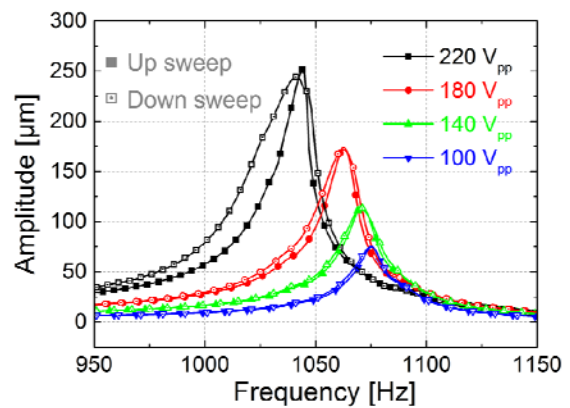


Figure 10: Frequency response curves of the miniaturized design with “center mass”.

REFERENCES

- [1] D. Roggenkamp, W. Jessen, W. Li, M. Klaas, W. Schroeder, “Experimental investigation of turbulent boundary layers over transversal moving surfaces”, *CEAS Aeronautical Journal*, pp. 1-14, Springer 2015.
- [2] Y. Du, G.E. Karniadakis, “Suppressing wall turbulence by means of a transverse traveling wave”, *Science*, vol. 288, no. 5469, pp. 1230- 1234, 2000.
- [3] C. Pickel, D. Sonnemann, C. J. Kaehler, “On the efficiency of active flow control with pneumatic jets at Mach numbers between 0.3 and 0.7”, *Experiments in Fluids*, vol. 55, no. 4, pp. 1-10, 2014.
- [4] D. Haller, A. Paetzold, N. Goldin, S. Neiss, F. Goldschmidtboeing, W. Nitsche, R. King, P. Woias, “Cymbal type piezo-polymer-composite actuators for active cancellation of flow instabilities on airfoils”, in *Digest Tech. Papers Transducers’11 Conference*, Beijing, June 5-9, 2011, pp. 494-497.
- [5] R.J. Adrian, C.D. Meinhart, C.D. Tomkins, “Vortex organization in the outer region of the turbulent boundary layer”, *Journal of Fluid Mechanics*: Cambridge University Press, 2000
- [6] I. Kovacic, M.J. Brennan, *The Duffing equation: nonlinear oscillators and their behavior*, John Wiley & Sons, 2011.
- [7] M. B. Mansoor, S. Koeble, P. Woias, F. Goldschmidtboeing, “Resonant actuation concept for the manipulation of upper turbulent boundary layer”, in *MikroSystemTechnik Kongress’15*, Karlsruhe, October 26-28, 2015, pp. 302-305.
- [8] A.W. Leissa, *Vibration of plates*, (NASA-SP-160), Washington, DC: United states government printing office, 1969.
- [9] J. Hadian, A. H. Nayfeh, “Modal interaction in circular plates”, *Journal of Sound and Vibration*, vol. 142, no. 2, pp. 279-292, 1990.
- [10] S. Koeble, M. B. Mansoor, P. Woias, F. Goldschmidtboeing, “Miniaturisierte Hochfrequenz Aktoren zur Beeinflussung der oberen turbulenten Grenzschicht”, in *MikroSystemTechnik Kongress’15*, Karlsruhe, October 26-28, 2015, pp. 769-772.

CONTACT

*M. B. Mansoor, tel: +49-761-20367494;
mansoor@imtek.de