DeMaMech Exchange Program Report

Feb. 2006 – July 2006

Katholieke Universiteit Leuven (KUL)

Tatsuya KEIDA

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2. Executive Summary

During 5 months' exchange study at Katholieke Universiteit Leuven, I was working on one research project under Prof. Dominiek REYNAERTS. Besides research project, I was taking 6 weeks English course which was focusing on academic English writing.

The topic of my research project was about investigation of the micro turbine rotor, which was related to the Belgian PowerMEMS project. Although micro turbine rotor requires high rotational speeds, there are many difficulties under desirable operational condition. The specific aim of this research was to investigate the behavior of high rotational speed operated micro-turbine rotor, therefore, I conducted the measurements of whirl vibration of balanced turbine rotor and the calculations of whirl vibration behavior. Before dealing with the measurements and the calculations, I have done some literature reviews and improvements of our measurement setup as well. So, through this research project, I was able to experience almost all elements of mechanical engineering studies; reading materials, designing, measurement and calculations.

Talking of my residence, I was living in a dormitory of which room I took over from former DeMaMech exchange student who was just going back to Japan when I arrived in Leuven. There were approximately 40 students living in my dormitory sharing kitchen and bathroom; almost half were Belgian students and the rests were exchange students.

After finishing my research project at KULeuven, I had an opportunity to attend at DeMaMech student workshop and a part of DeMaMech joint project meeting in TUDelft from July 10th to July 12th with some other DeMaMech exchange students from EU's university. I helped some preparations for joint project meeting with other EU's students during the workshop. At the joint project meeting, the all-participating students, including me, gave the presentation about what they have done and experienced during their DeMaMech exchange program. This workshop and joint project meeting was really nice experience for me because I was able to deliver my presentation in front of many professors in English and I could meet and talk with other DeMaMech exchange students from EU as well as many professors and other panelists.

3. Travel Schedule

From 31/January/2006 until 9/July/2006

4. Research and Lectures

- Research -

I was working on my research project almost every weekday from 10am to 7pm during saying at KULeuven. But, of course, the working time and day were not fixed that I could do other things which I had to do during the day and possible to work later on.

Actually there were some differences on laboratory environment as compared with my lab in Japan; basically, PhD students are the main members of lab while MSc students conduct their research project with help and guidance of PhD students or professors while they do not have their own specific office or place to do their disk work. However, in my case, I got a desk in as same room as my supervisor at the beginning, but after new PhD student arrived to our lab, I had to move to the laboratory room where several experimental setups are installed. (In fact, the lab room was nice in hot days because they had air-conditioner in order to keep room temperature at 20℃ for experimental setups while offices in Belgium normally have no air-conditioner.) I would say that it was not easy to meet many MSc students because I seldom share the time, place or experiment with them. Instead, I met with my supervisor or PhD students who is elder than me and had more knowledge and skills about the research, which was nice opportunity to inspire myself.

The topic of my research project was about investigation of the whirl behaviour of a micro-turbine rotor. This topic was one of the researches of Belgian PowerMEMS project and had already been developed by my supervisor when I got there. Although, at that time, the test-setup was almost ready for measurement, we have found out that there were few problems on test-setup and the modification on test-setup was necessary for better measurement result. Therefore, I conducted few modifications on test-setup, and later on, I did the measurement as well. Moreover, I tried to predict the behaviour of turbine rotor by calculations using MATLAB®. The details of my research project are described in following paragraphs.

Title: [**Investigation of the whirl behaviour of a micro-turbine rotor**]

Air bearings can be one of the alternatives for supporting the rotor in micro gas turbine because they tolerate the high temperatures and cause less frictional losses. Even though air bearing seems to have several advantages, there are some problems for high-speed operation such as rotor vibration due to critical speeds or self-excited instabilities (half-speed whirl). Therefore the aim of this research is to reduce the rotor vibration on rotor and to lead high rotational speed by applying appropriate balancing method. We will also concentrate on investigation of rotor behaviour during high-speed

operation. In order to achieve these aims, I have mainly followed three steps as follows;

1. Modification of test-setup for repetitive result
2. Measurements of whirl vibration on balanced rotor
3. Prediction of whirl vibration behavior by calculations (using MATLAB®)

[Modification of test-setup for repetitive result]

The crucial problem of the previous setup was that the measurement results were not repetitive after disassembling and re-assembling the test-setup. It meant that some uncertain elements were lying on the test-setup in terms of assembly. Actually, on the previous setup, the covers seemed not well design for aligning two split bearings in a proper position; both covers were fixed to both sides of housing while the length of cylindrical of both covers were determining the alignment of the two split bearings. If the length of the cylindrical part is longer than the design specification, the edge of the cylindrical parts of both covers will interfere with each other.

In order to achieve proper alignment of the two split bearings in a repetitive way at every assembly, one precise reference edge is necessary and, at the same time, the two split bearings are need to be completely touching this reference. Therefore, we have made one cover with reference edge at one side and a second flexible movement cover, which is pushing the two split bearing parts towards reference edge, on the other side. For the reference side cover, we have machined new cover with precise length of the cylindrical alignment part. The flexible movement cover is consists of an inner cover, wave spring and outer cover. The inner cover is touching the two split bearings while pushed by a wave spring, at the same time, the outer cover is pushing the wave spring and while itself is fixed to the housing by screws.

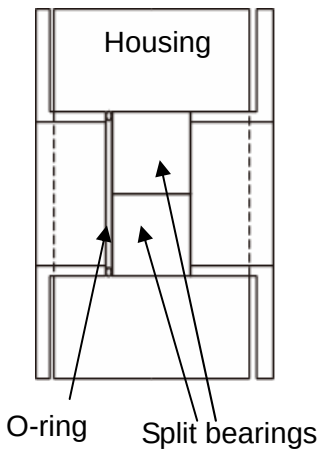

Fig. 1 The previous test-setup

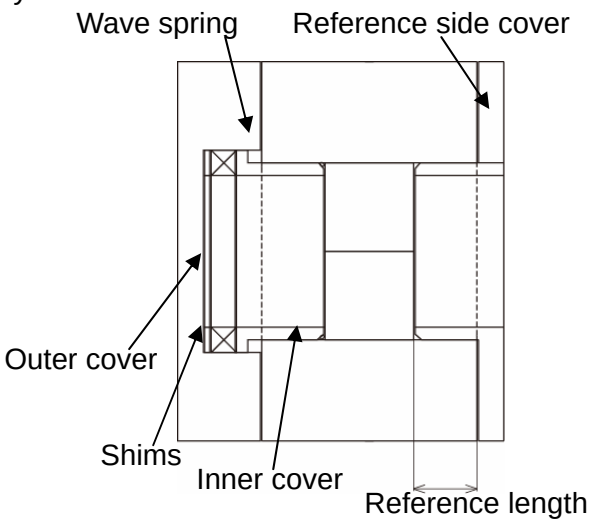

Fig. 2 The modified test-setup

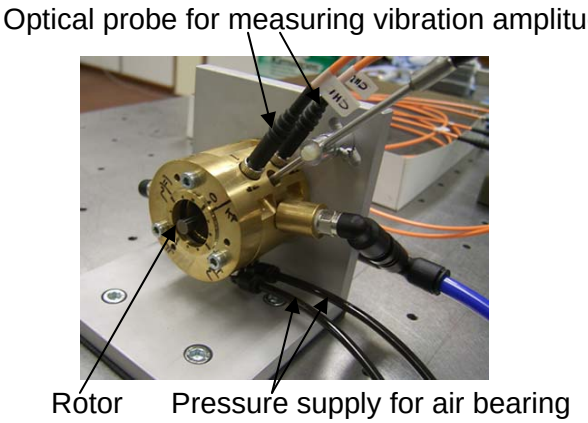

Fig. 3 Test-setup appearance

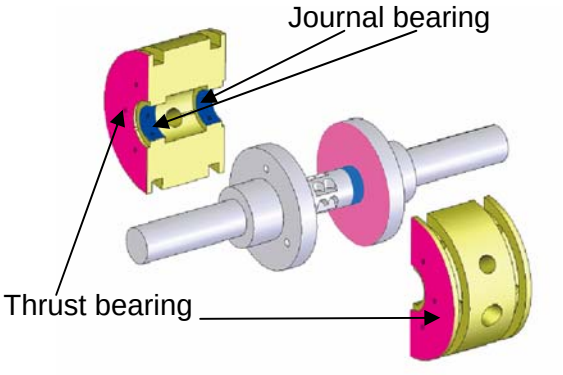

Fig. 4 3D-CAD model of rotor & split bearing

[Measurements of whirl vibration on balanced rotor]

The existing imbalance of rotor causes the imbalance force;

$$F = m\varepsilon\omega^2$$

where m is the mass of rotor, ε (eccentricity) is misalignment of center-of-gravity from axis of rotational axis and ω is the rotational speed of shaft. This force becomes main source of imbalance response on rotor. Moreover, the rotor has larger amplitude near the critical speeds (resonance frequencies) compared with other speed regions. In our case, our target speed is above the critical speeds so that the maximum vibration amplitude must be lower than the clearance of the air bearings otherwise the rotational speed never pass through the critical speeds. So we tried to bring down the amplitude of whirl vibration applying the balancing method called ‘Two-plane balancing with influence coefficients’ in order. Several trails of this balancing method lead to bring down the vibration amplitude below the bearing clearances and to pass through above the critical speeds.

After balancing the rotor, the run-up and coast-down whirl vibration measurements were conducted from 50 Hz up to 1600 Hz (attainable maximum speed). Since the stiffness and damping rate of the air bearing is depend the pressure supply of air bearings, I was interested in the effect of changing pressure supply on the measurement result. So the whirl vibration amplitude and phase of rotor disks were measured at several pressure supply conditions (P = 3, 5, 7bar relative) of air bearings (Fig. 5, 6, 7). The amplitude measurement results indicate that there are certainly two peaks corresponding to critical speeds of turbine rotor; in our case, the first peak and the second peak is related to the conical movement and the cylindrical movement respectively. The two peaks are closer at lower-pressure condition whereas the peaks

are easily confirmable at higher-pressure condition. Also the critical speeds become higher at higher-pressure supply, which can be explained that higher-pressurized air bearings have higher stiffness. The critical speeds identified from these results are summarized in Table 1.

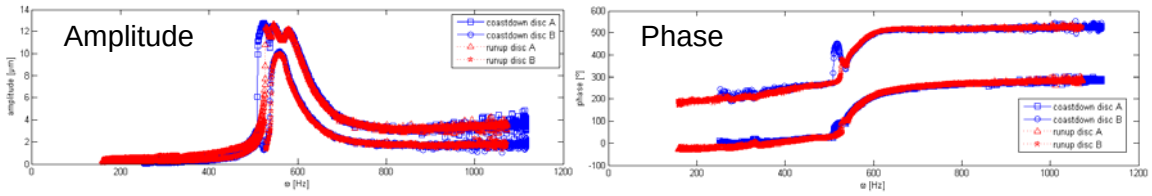

Fig. 5 Coast-down / Run-up measurement at P = 3bar relative

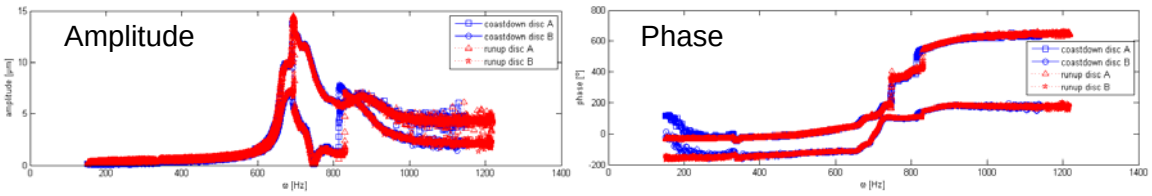

Fig. 6 Coast-down / Run-up measurement at P = 5bar relative

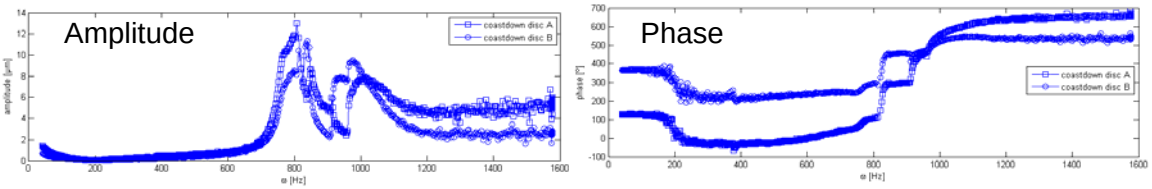

Fig. 7 Coast-down at P = 7bar relative

	P = 3bar	P = 5bar	P = 7bar
Conical mode ω_{con} [Hz]	470	690	800
Cylindrical mode ω_{cyl} [Hz]	560	810	900

Table 1 Critical speeds at different pressure supply

[Prediction of whirl vibration behavior by calculations (using MATLAB®)]

We tried to predict the run-up (coast-down) forced vibration behaviour, especially the two critical speeds (conical and cylindrical mode) and its amplitudes (peaks). Since an air bearing can be modelled as a spring and damper, the whole set up was modelled as a mass-spring-damper system.

Forced whirl vibration can be simulated by frequency response analysis using the transfer function of equation of motion (input as imbalance force or torque and output as movement of shaft);

$$\mathbf{X}(j\omega) = \mathbf{H}(j\omega) \cdot \mathbf{F}(jw) = \frac{\mathbf{F}(jw)}{-\omega^2\mathbf{M} + \mathbf{K} + j\omega\mathbf{C}}$$

In our case, however, the value of transfer function is not constant at each rotational speed because the stiffness and the damping rate of air bearings vary with rotational speed as well as perturbation frequency of shaft vibration. Therefore, before calculating forced whirl vibration, the bearing calculation was at first conducted for preparing the stiffness and the damping rate at each rotational speed and at each perturbation frequency.

The calculation was made at same pressure condition as the run-up measurement; P = 3, 5, 7 bar relative (Fig. 9, 10, 11). It is possible to confirm two certain peaks on calculated amplitude while the measurement gives complicated shapes between and around two critical speeds. It appears that the two vibration modes are not completely independent. Comparing calculated critical speeds to measured one as table 2, we can say that the calculation can be one of the guidance of predicting critical speeds.

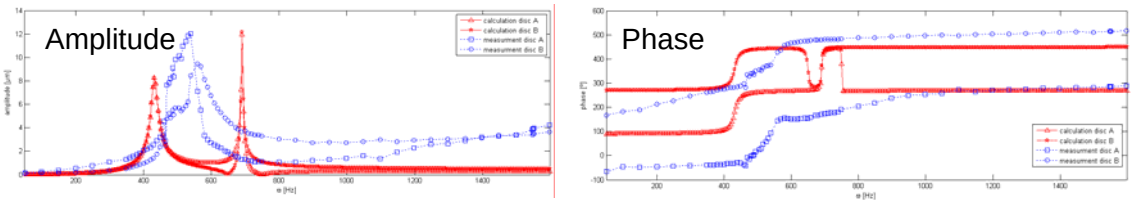

Fig. 9 Imbalance response calculation at P = 3bar relative

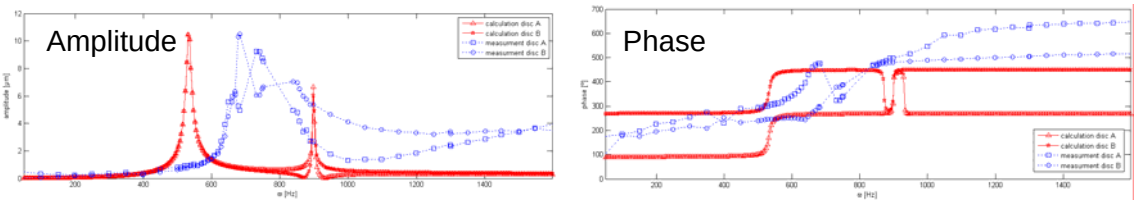

Fig. 10 Imbalance response calculation at P = 5bar relative

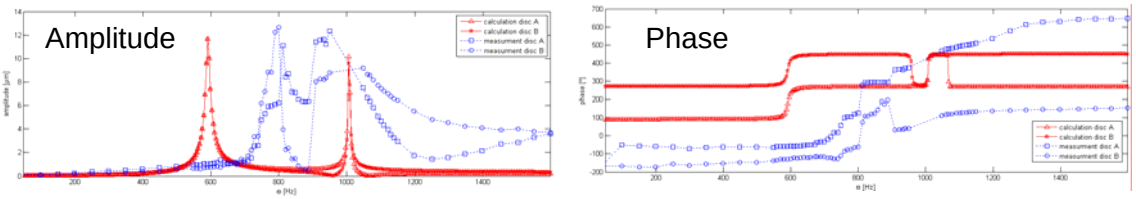

Fig. 11 Imbalance response calculation at P = 7bar relative

	P = 3 bar	P = 5 bar	P = 7bar
Conical mode ω_{con} [Hz]	432 (-17%)	532 (-25%)	591 (-27%)
Cylindrical mode ω_{cyl} [Hz]	691 (+23%)	897 (+10%)	1005 (+10%)

Table 2 Calculated critical speeds on forced vibration analysis

- Lecture -

I was not following any regular course during the semester because it was not easy for one semester-exchange students to take the normal lectures in KULeuven comparing with DTU or TUDelft. However, there are many chances to participate language courses because there are several kinds of language academy in KULeuven. Of course, I could learn Dutch, English, and French etc. with several kinds of levels and contents but some of them you have to pay some tuition.

I followed English course for academic writing called “Academic English for Master's Students” provided by *KULeuven Institute of Modern Languages***.** This course was only two 3 hours lectures a week for total 6 weeks and the tuition was around 200EUR including text book. When I was registering the course, I thought the tuition was bit expensive, but, after the whole class, I would say that it was worth paying for this academic English because I was satisfied with the contents; the course was focusing on academic writing English with solid and fruitful contents. I think it is not easy to take similar course in Japan.

The course was focusing on not only grammar or words but also the structure, style and lay-out of academic report. This kind of lecture was new for me, I mean; I have not taken this kind of lecture even in my mother tong. During this course, there were normal lectures and some practice as well as main four assignments which were about “Writing formal e-mail”, “Writing critical reviews”, “Writing Introduction for own report” and “Writing Abstract for own report”. Of source, all these assignments were checked and corrected by our teacher so I was able to know what is my problem on my writing. Also writing my own Introduction or Abstract was really practical assignment.

5. Exchange student life

My exchange student life in Lenven was started from 31st July 2006. Before coming to Leuven, I was studying at DTU in Denmark as first staying university for my DeMaMech exchange so I directly moved from Copenhagen to Leuven.

It is often said that the first difficulty for exchange student in KULeuven is house hunting. Normally, the housing office of KULeuven dose only arrange temporary accommodation not permanent one so the students have to look for a place to live by themselves from the list of vacant accommodations after arriving at Leuven. But, in my case, I was really lucky because I was able to take over the room of dormitory from former DeMaMech exchange student from Japan who was just going back when I

arrived at Leuven. This was really helpful for me to start my exchange student life in Leuven.

My dormitory was called “American college” and located at 5 min walk from the center of town. There were approximately 40 students, half were Belgian and the rest were international student, with many varieties such as from bachelor students to PhD students or post doctors. We all had our own room but had to share the kitchen, shower and toilet. I would say that the kitchen was not perfectly clean because all the students were using one big kitchen. However, there was living room with TV and ping-pong table next to kitchen so we could enjoy the time whenever we want.

In the beginning of the semester, there were welcome and introduction days for International students called “Orientation days” organized by KULeuven. During these days, there were introduction session, simple Dutch lessons, welcome party and day trip to Gent. It was nice days for me but I would say the introduction days in DTU was more well organized and much more easier to meet with new friends. Actually, it was not so easy for me to find real close friends in KULeuven. One of the reasons can be that I was not attending regular course. Also the fact that each student in my dormitory has different interest or situations could be another reason. Although I did not have specific close friends there, I meet nice people with wide varieties.

The living environment in Leuven was really nice and fantastic for me because I loved the scenery of the town with many old and beautiful buildings such as churches and city hall. Also there are enough shops in the town so it was enough convenient to live. (Of course, Japan is much more convenient from the point of view of opening hour of shops, but once I get used to it, it was not big problem.) The favorite place in Leuven is botanical garden. I often went there because I could relax myself with many flowers and trees and even I preferred to feel the transition of season from winter to spring and then to summer. Moreover, I also liked the scenery around the campus of engineering located in Heverlee (the next town of Lueven) because there are old buildings (now used for one of the faculties of KULeuven) with nice green fields and small rivers and small artificial ponds. Also I would say that the nice spring and summer days with long daylight made me feel even better.

Of course, I made several trips during weekends in Belgium as well as other European countries such as the Netherlands, Luxembourg, Germany, Italy, Monaco, Switzerland and Spain. I really like motor sports so I went to see the WRC in Spain and the Formula 1 in Monaco. Moreover, I went to see few Belgian rally championship as well. It was really fantastic and I really enjoyed them. Talking of Belgium, the country is not by large so that I could easily get to other cities by trains or by rent-a-car. The

interesting thing of Belgium is that they have several kinds of cultures in small country, especially they have two regions; one is Flemish (Dutch speaking part) and the other is Wallonia (French speaking part). Leuven was Flemish part so every one was speaking in Dutch and most of people can speak English but, if I go 30min towards south by car, I am in Wallonia part so every people is speaking in French and not all people can speak in this region, which was little bit hard to communicate with people. Although I know the fact that Belgian has mainly two languages in one country by high school's geography class, it was still sensational for me to experience this difference. By the way, I would highly recommend to go the medieval city Brugge because it still has really nice old buildings with many beautiful canals and so on. But there are, of course, many cities and places to visit in Belgium.

6. Summary

I would like to say that I had really nice and fantastic study and life in Leuven. Actually, I am satisfied with my research project because I have learned many things (not only theory but also practical elements as well) through this project and also my supervisor helped and guided me a lot on my project. Although I had hard time to find real close friends, I met many people with many varieties so that I could realize many new ideas, which I hardly find in Japan.

Through this whole exchange program, I had many chances to meet with different cultures, new idea or perspective, different education system and so on. I think I had really precious experiments that I cannot meet in Japan. Moreover, now I feel that I have fewer barriers using English comparing with before going to Europe so I would like to keep on improving my English in Japan. I think I can never forget this fantastic exchange student life in my whole life.