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Robustness Evaluation of Internal Model Principle-based Controller in a Magnetically Actuated Surgical System

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***Abstract*— The local magnetic actuation (LMA) surgical method has gained popularity among medical practitioners and researchers in the field of abdominal surgery. The procedure requires the use of magnets on both sides of the abdominal cavity to anchor devices onto abdominal wall while magnetic sources on the external side generate actuation signals to drive robotic manipulators inside the cavity. Due to the transmission of magnetic fields across the abdominal wall and the interactions among multiple LMA units within the vicinity, magnetic interference will affect the performance of the intended rotor driving the degree-of-freedom (DOF) on the robotic manipulator. Since the disturbances due to the neighbouring magnetic sources are found to be sinusoidal signals with a known frequency, they can be rejected by using the internal model principle (IMP) technique. The disturbance due to the abdominal wall tissue dynamics during magnetic actuation causes oscillations on the internally anchored surgical device, which has generally been ignored in the implementation of LMA application. The focus of this paper is to provide a model that incorporates tissue dynamics in the LMA system. Moreover, the robustness of IMP controller in the presence of tissue dynamics is discussed. Simulations are performed and the results demonstrate effective rejection of both disturbances when they are taken into account in the IMP disturbance model.**

I. INTRODUCTION

Recently, local magnetic actuation (LMA) techniques for abdominal surgery have been studied for its potential in replacing rigid mechanical transmission on conventional laparoscopic devices with magnetic linkages [1]. As illustrated in Figure 1, the concept of magnetic coupling is used to anchor the internal devices onto the abdominal wall within the insufflated abdominal cavity while still allow the positioning of the anchoring location within the abdominal cavity [2], [3]. Actuation can also be produced by generating the required actuating magnetic field through sources external to the abdominal cavity, to regulate the motion and torque of a permanent magnet rotor on the internal device (inside the abdominal cavity) [4], [5]. The resulting actuation of each of the permanent magnet rotor is used to drive individual degrees of freedom in an otherwise passive surgical (robotic) mechanism inside the abdominal cavity [6]. As each external source of magnetic field is used only to actuate an internal rotor directly on the other side of the abdominal wall (see Fig. 1), this is then referred to as Local Magnetic Actuation (LMA) approach, as opposed to using a global magnetic field such as seen in a magnetic resonance imagining (MRI) machine, Octomag [7] and the Stereotaxis system [8].

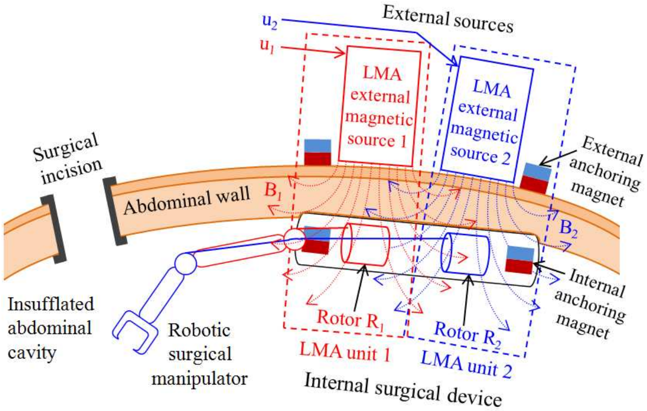

Fig. 1: An illustration of a two-DOF LMA system actuating a robotic surgical manipulation. The rotors, placed on the inside of the abdominal wall, are driven by electromagnet stators 1 and 2 located external to the abdominal wall, respectively. These stators are driven by the actuating commands, u_1 and u_2 which provide magnetic fields B_1 and B_2 across the abdominal wall to produce rotational motions on rotors R_1 and R_2, respectively. Disturbance happens when B_1 also affects R_2 and B_2 affects R_1.

It is noted that there is a controller for each individual LMA set, which is usually a simple PI controller [5], [9]. The design of PI controller is usually model-based without taking disturbances into consideration. There are a few input disturbances coming from the mechanical setting of LMA. These disturbances results from unintended dynamics excited by the actuation command of the system.

The first disturbance is due to actuating magnetic field intended for one rotor affecting other rotors in its vicinity.

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Each stator-rotor pair is used to drive one degree-of-freedom (DOF) on a robotic surgical manipulator. For many surgical tasks, multi-DOF robotic manipulation is required, hence requiring multiple LMA units to be employed. The presence of multiple sources of (actuation) magnetic field within the vicinity of each other (the overall system must fit on a human subject's abdomen) causes a crosstalk of magnetic field intended for one rotor to disturb other rotors in its vicinity [10]. As these disturbances are observed to have the form of sine waves with known frequency, the internal model principle (IMP) based technique was used to eliminate the effect of such disturbances [11].

The second disturbance is due to the unmodelled dynamics of the abdominal wall, to which the LMA system is anchored, magnetically to an external set of magnet (see Figure 1). It is often assumed that the LMA is anchored onto a stationary / rigid platform, however it is clear that the abdominal wall tissue is of viscoelastic nature [12]. It is noted that the magnetic field from the external actuator produces not only the intended moment to rotate the internal rotor, but also produces forces on the rotor in other degrees of freedom, which forms the disturbance forces. The actuation magnetic field is sinusoidal in nature (in order to produce cyclical motion of the rotor) results in sinusoidal behaviour of the disturbance forces, hence creating an oscillation on the internal LMA platform as the rotor is anchored onto the non-rigid abdominal wall.

With the knowledge that the disturbance due to the tissue dynamics exists, the focus of this paper is to investigate the robustness of the proposed IMP with respect to this disturbances. The contribution of this paper is two-fold. The first one is that the tissue dynamics is incorporated into the model of IMP to capture the influence of the abdominal wall. Secondly, the evaluation of the proposed IMP when taking into account the tissue dynamics using numerical simulations.

The remainder of the paper is organised as follows. Section II describes the model of the LMA system in the presence of the disturbances. Controllers design including IMP based design is revisited in Section III. Section IV presented the numerical simulations performed on the LMA system, demonstrating the efficacy of the IMP controller with discussions in Section V. The study is then concluded in Section VI with some recommendations for future works.

II. SYSTEM MODELLING IN THE PRESENCE OF DISTURBANCES

The block diagram of LMA control system in the presence of two disturbances can be seen in Figure 2. The first disturbance $d_1(t)$ exists due to the neighbouring LMA unit while the second disturbance $d_2(t)$ comes from the tissue dynamics during magnetic actuation from the external magnetic sources.

A. LMA system

The model of the LMA system has been identified in [11] as a linear-time-invariant system (A,B,C) and can be represented in the state space form:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{1}$$

where state $x = \omega$ and the system input, $u = i_{q_{ref}}$, and the following state space matrices:

$$A = -\frac{b}{J}, \quad B = \frac{\psi_R}{J}, \quad C = 1. \tag{2}$$

where ω denotes the angular velocity of the rotor, $i_{q_{ref}}$ is the reference i_q current to the LMA system, J and b are the total moment of inertia and the friction coefficient of the rotor respectively, and ψ_R is the magnetic flux at the rotor.

B. Disturbance due to neighbouring LMA unit, d_1

As noted in the introduction, there are two main systematic disturbances that needs to be handled in an LMA system. These disturbances occur as an inherent part of the LMA approach. The first is the disturbance is generated due to neighbouring unit, i.e. LMA Unit 2, known as d_1. In [11], this disturbance was taken into consideration for a multi-DOF LMA configuration because of the resultant magnetic interaction at the point of the rotor, R_1. This d_1 was observed to be of sinusoidal waveform with a known frequency, though the amplitude and the phase are unknown.

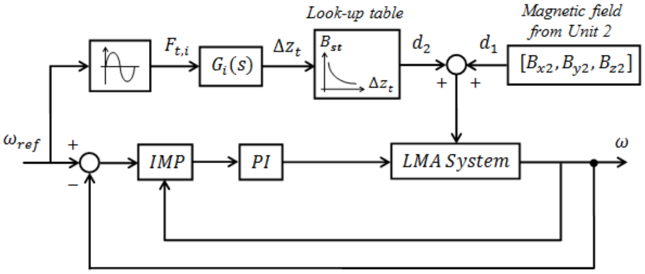

Fig. 2: Block diagram with two input disturbances into the LMA where d_1 is the disturbance or magnetic interference due to the neighbouring LMA unit in term of its x, y and z components, i.e. B_{x2}, B_{y2}, B_{z2}, and d_2 is the disturbance due to the tissue dynamics which affects the magnetic field, B_{st} at rotor, R_1. This B_{st} is obtained from the look-up table of the displacement, Δz_t and B_{st} relationship validated in [13]. The tissue displacement, Δz_t is the output of the tissue transfer function model, $G_i(s)$ with the force, $F_{t,i}$ generated by the corresponding stator unit required to perform surgical tasks as the input signal.

The frequency of the disturbance aids the design of the observer to estimate the disturbance in the IMP controller designed in [11] which demonstrated effective suppression of d_1.

C. *Disturbance due to the (non-rigid) abdominal wall tissue dynamics, d_2*

Apart from the disturbance due to the magnetic interference caused by neighbouring LMA unit, there is another systematic disturbance inherent in the LMA approach. As the internal surgical device is anchored magnetically onto the abdominal wall, any displacement in the non-rigid tissue of the abdominal wall would translate to unmodelled displacement onto the internal LMA device.

In [12], the dynamics of the abdominal wall tissue has been investigated to produce disturbance onto rotor R_1 as well. In this paper, as shown in Figure 3, it is treated as another input disturbance onto the LMA system.

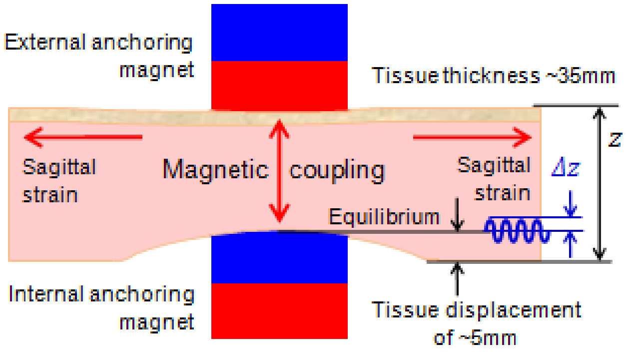

Fig. 3: Schematic diagram of the tissue cross section, illustrating the equilibrium state of the tissue when magnetically "clamped" or anchored. The tissue experiences perturbations in the direction normal to the anchoring axis, Δz about the equilibrium state due to external excitation signals [11]. (Note: the amount of tissue compression in the illustration is exaggerated for visualisation purpose.)

This disturbance, d_2 affects the z-component of the resulting magnetic field at the point of the rotor due to the tissue oscillation about its equilibrium, which comes from the sinusoidal frequency of the actuation signal from Unit 1 as shown in Figure 3. The tissue dynamics can be represented as a transfer function. The input of this transfer function is a sinusoidal form of the force $F_{t,i}$ for surgical task (e.g. lifting liver tissue requiring approximately 5N [6]) which is affected by the frequency of the reference signal to its corresponding unit 1. The output of this transfer function is Δz_t, which is the displacement experienced by the abdominal wall tissue. The incorporation of the transfer function model of the tissue [12] enables the changes in the magnetic field to be determined through the look-up table derived from the displacements versus magnetic field relationship validated in [13]. The magnetic field obtained from the look-up table then get superpositioned with the magnetic field contributed by LMA Unit 2 to get the resultant magnetic field at the point of the rotor.

Three different anchoring configurations were considered in [12] for different operational points as shown in Table I and the general transfer function model identified in [12] is written as below:

$$G_i(s) = \frac{k_{1_i}}{\tau_{1_i}s+1} + \frac{k_{2_i}}{\tau_{2_i}s+1}e^{-\theta_i s}, \quad i = 1,2,3. \tag{3}$$

with i =1, 2, or 3 denoting the anchoring sets, $k_{1,i}$ and $k_{2,i}$ are the response gains for each "i", $\tau_{1,i}$ and $\tau_{2,i}$ are the time constants, and θ_i is the time delay in the tissue response, along with the corresponding set of model parameters listed in Table II.

TABLE I: Configuration of anchoring magnet sets used in analyses [12].

Anchoring set i	Anc Force (N)	Internal magnet	External magnet
1	2	50x50x12 mm	10x10x10 mm
2	4.7	38x38x12 mm	20x20x12 mm
3	7	50x50x12 mm	20x20x12 mm

III. CONTROL OBJECTIVE AND CONTROLLER DESIGN

During operation, the LMA system, i.e. the rotor, is required to track a reference velocity, hence an integral controller is incorporated to regulate and stabilise the system. A standard PI controller is used (see more details in [11]). In order to handle input disturbances, IMP based control design is used. In [11], the disturbance d_1 has the form of sinusoidal waves with known frequency. An IMP loop is incorporated into a standard PI controller (i.e. known as IMP_{d1} as described in Sec. IV).

TABLE II: Best fit parameters approximation for the tissue model for all three anchoring sets [12].

Anchoring set i	k_1	τ_1	k_2	τ_2	θ
1	1.715	0.2	0.345	0.283	2.783
2	1.04	0.083	0.34	0.2	1.067
3	0.733	0.45	0.3	0.133	0.25

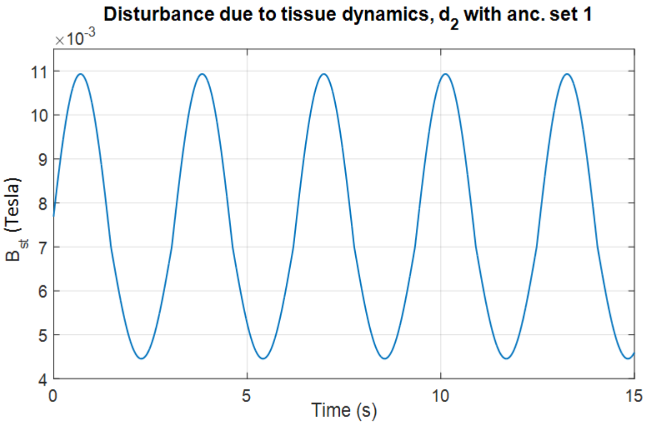

Fig. 4: Disturbance due to the tissue dynamics d_2 in sinusoidal form simulated with 2 rad/s reference, ω_{ref} for simplicity of visualisation.

The role of IMP is to use some knowledge of the disturbances to cancel the influence of disturbances [14], [15]. More precisely, the model of input disturbances will be used in the state space representation of the system. If the state of the disturbance is able to be observed from the output measurements, by incorporating an appropriate observer, the effect of the disturbances will be cancelled.

As discussed in [11], the influence of the disturbance d_1 can be easily cancelled using IMP. The performance of the proposed IMP was validated via experiments. However, the disturbance d_2 is more complicated. As can be seen in the diagram presented in Figure 2, the disturbance d_2 comes from the sinusoidal force input, which has the same frequency as the reference, ω_{ref}. The transfer function $G_i(s), i = 1,2,3$ is a stable linear time invariant with/without delays with fast transient responses (or small time constants). This indicates that, at steady state Δz_t is also a sinusoidal signal with the same frequency, but different amplitude and phase. However the look-up table of the mapping from Δz_t to B_{st} is not a linear. Thus, the disturbance d_2 is a not periodic signal. Moreover, due to the existence of nonlinear look-up table, the overall system (IMP, disturbances and linear controller) is not a linear system.

As the disturbance d_2 is not a sinusoidal signal, IMP cannot be used to completely cancel its influence to the output of LMA. As the PI controller and IMP both have some robustness, this paper first investigates the robustness of the proposed PI controller and IMP [11] with respect to the tissue dynamics when they are incorporated into the model of LMA. It is noted that in the experimental setup in [11], the tissue dynamics were not included as it is considerably challenging to arrange the experiments for the LMA approach with consideration of the tissue dynamics without going into animal or human trials. Hence, simulation based techniques are used to evaluate the performance of the proposed controller (PI and IMP) at this stage.

Furthermore, as the look-up table is almost linear, the steady-state of d_2 is almost like sinusoidal with a known frequency. By using a simulation model, which consists of the LMA and two disturbance models, it is shown that the disturbance d_2 can be approximated as a sinusoidal signal (as visualised in Fig. 4) with the frequency ω_{ref}. It is noted that even though the simulation model cannot fully capture the LMA system, each component in the simulation model is validated via a large number of experiments [10], [11], [13], [16]. Hence, the simulation model can be use to characterize some features of the disturbances. Since the disturbance d_2 can be approximated as a sinusoidal signal with the frequency ω_{ref}, similar to the way of dealing with d_1, d_2 can be incorporated in the IMP loop as well (i.e. $IMP_{d1,d2}$ as described in the following section, Sec. IV).

IV. NUMERICAL SIMULATIONS

Simulations are performed with the settings emulating the abdominal surgical environment as per [11], with the closest distance between stator units. The role of simulations is to show the robustness of IMP, which designed for d_1, with respect to the disturbance d_2 coming from tissue dynamics. To simplify the notation, this IMP is called IMP_{d_1}.

On the other hand, a new IMP is designed based on d_1 and approximation of d_2. This IMP is called IMP_{d_1,d_2}. As the approximation errors exist, the simulation results also demonstrate the robustness of IMP_{d_1,d_2}.

Three different reference speeds, i.e. 60rad/s, 80rad/s, 100rad/s are simulated in four cases as listed below:

- Case 1: Only LMA unit 1 is switched on to run at the given reference speed, including tissue dynamics in the LMA system.
- Case 2: LMA unit 1 remains on and LMA unit 2 is now switched on, producing magnetic interference or disturbance onto rotor R_1.
- Case 3: Both LMA units remain on and IMP_{d_1} is now initiated, to observe the suppression of the disturbance due to unit 2 onto R_1, as well as the disturbance due to the tissue dynamics.
- Case 4: Both LMA units remain on and IMP_{d_1,d_2} is now initiated, to observe the suppression of the disturbance due to unit 2 onto R_1, as well as the disturbance due to the tissue dynamics.

The simulations are executed in this order to enable the comparison and evaluation of the the efficacy of the IMP controller onto the system for different anchoring sets and at three different reference speeds to the rotor, R_1 when the tissue dynamics is taken into consideration. The simulation results are shown in Figure 5 and the performances of the IMP controllers (i.e. IMP_{d1} and $IMP_{d1,d2}$) are presented in Table III.

V. DISCUSSIONS

After taking the tissue dynamics into consideration in the system model, the performance of the rotor is observed to affect the response from the beginning (see Figs. 5). The frequency of the oscillation due to the tissue dynamics approximates the frequency of the signal transmitted by the corresponding stators as discussed in Section II. The oscillation about the equilibrium state of the anchored tissue causes displacement about that point, i.e. Δz and in turn impacts on the resultant magnetic field in sinusoidal nature. From Figure 4, the amplitude of d_2 is approximately 0.0033 Tesla (illustrated with 2 rad/s simulation to simplify visualisation). The effect of d_2 in the output is relatively small, indicating some attenuation of the disturbance by the tissue properties itself as it is noted that the transfer function of the tissue dynamics replicates a low pass filter. Thus, when ω_{ref} is arbitrarily large, the low pass filter will filter out some amount of disturbances.

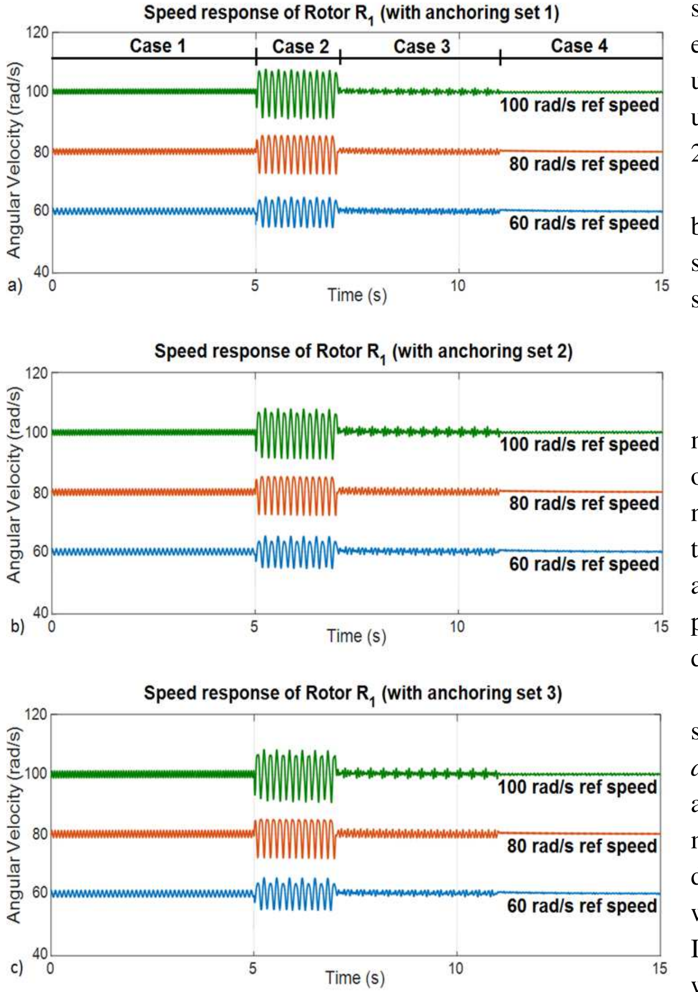

Fig. 5: Simulation results on the LMA system with four cases, including the implementation of IMP_{d1} (i.e. Case 3) and $IMP_{d1,d2}$ (i.e. Case 4) for comparisons with reference speeds of 60rad/s, 80rad/s and 100 rad/s on rotor R_1: a) with anchoring set 1 b) with anchoring set 2, and c) with anchoring set 3.

Nonetheless, when only IMP_{d1} is implemented (i.e. in Case 3), the disturbance due to the tissue dynamics is not fully suppressed. This is due to the lack of the tissue disturbance information in the IMP disturbance rejection scheme at this instance, though some amount of the disturbance has attenuated due to the inherent low-pass filtering nature of the tissue. On the other hand, when IMP_{d_1,d_2} which incorporated some approximated information of d_2 (i.e. in Case 4), better tracking performance and suppression of the disturbances are observed. Even though there is still steady state error due to the existence of approximation error, $IMP_{d1,d2}$ demonstrated the capability of suppressing up to 90% of the overall disturbances in Case 2 and also up to 37%, 64% and 65% in Case 3, for anchoring sets 1, 2 and 3, respectively, as presented in Table III.

It is noted that both IMP_{d_1} and IMP_{d_1,d_2} are designed based on a linear time-invariant LMA system, in simulation setting, the look-up table generates nonlinearity. Thus, the simulation results show the robustness of two IMP designs.

VI. CONCLUSION AND RECOMMENDATIONS

In local magnetic actuation (LMA) surgical devices with multiple units, except for the coupling effects between two or more sets, the tissue dynamics during external excitation needs to be considered in the design of appropriate controllers. These effect of neighboring LMA sets d_1 as well as the tissue dynamics d_2 are input disturbances. This paper presents a new LMA model that can take these two input disturbances into consideration.

The first disturbance d_1 was observed as a sinusoidal signal with a known signal while the second disturbance d_2 has some nonlinearity, though it can be approximated as a sine wave with the known frequency. Two internal model principle (IMP) controllers are used to deal with two disturbances. The first one only used the information of d_1 while the second one used the information of d_1 and d_2. It showed from simulations, that the first IMP can work with a reasonable performance. When some information of d_2 is used, even though it is not a sinusoidal signal, the IMP controller that uses its approximation can achieve better tracking performance. Future work also includes validating the simulation findings in experimental setup, when emulating the abdominal surgical environment is feasible.

TABLE III: Performance evaluation of the IMP controllers on the LMA system with the incorporation of the tissue dynamics in the IMP model, with IMP_{d1} catering for only d_1 as well as $IMP_{d1,d2}$ catering for both d_1 and d_2 (numbers presented in terms of steady state amplitudes, e).

Anchoring sets (i)	Reference speed w_{ref} (rad/s)	Case 1 LMA unit 1 e_1 (rad/s)	Case 2 Units 1 & 2 e_2 (rad/s)	Case 3 IMP$_{d1}$ on e_3 (rad/s)	Case 4 IMP$_{d1,d2}$ on e_4 (rad/s)	Performances of cases %		
						4 vs 1 ($\frac{e_1-e_4}{e_1}$)	4 vs 2 ($\frac{e_2-e_4}{e_2}$)	4 vs 3 ($\frac{e_3-e_4}{e_3}$)
1	60	0.67	4.82	0.77	0.48	28.4	90	37.7
	80	0.63	5.94	0.71	0.42	33.3	92.9	40.8
	100	0.62	7.36	0.68	0.38	38.7	94.8	44.1
2	60	1.19	5.1	1.08	0.37	68.9	92.7	65.7
	80	1.05	6.21	1.11	0.32	69.5	94.8	71.2
	100	1.06	7.32	1.09	0.31	70.8	95.8	71.6
3	60	1.21	4.73	1.08	0.38	68.6	91.9	64.8
	80	1.17	6.51	1.15	0.35	70.1	94.6	69.5
	100	1.12	7.55	1.17	0.32	71.4	95.8	72.6

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